QCD NLO with Powheg Matching and Top Threshold Matching in WHIZARD

Jürgen R. Reuter, DESY

in collaboration with F. Bach, B. Chokoufé, A. Hoang, W. Kilian, M. Stahlhofen, C. Weiss

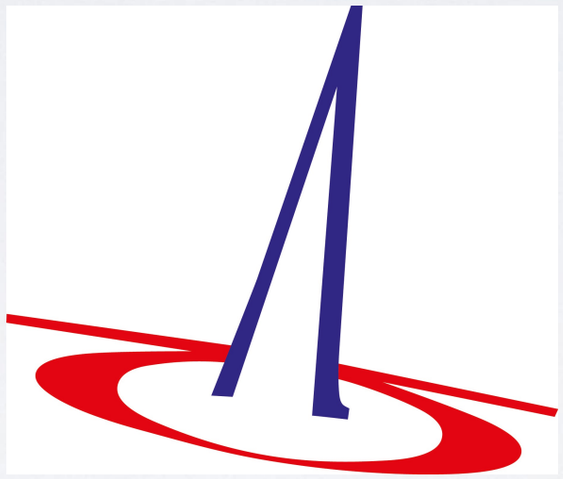
Outline of the talk

1) Introduction into WHIZARD

2) Fixed-order NLO automation &
POWHEG matching in WHIZARD

3) Top threshold in (N)LL (p)NRQCD matched to fixed order (N)LO in WHIZARD

1) Introduction to WHIZARD



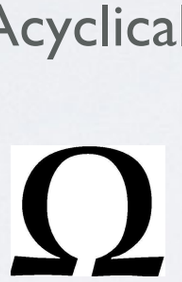
WHIZARD: Introduction

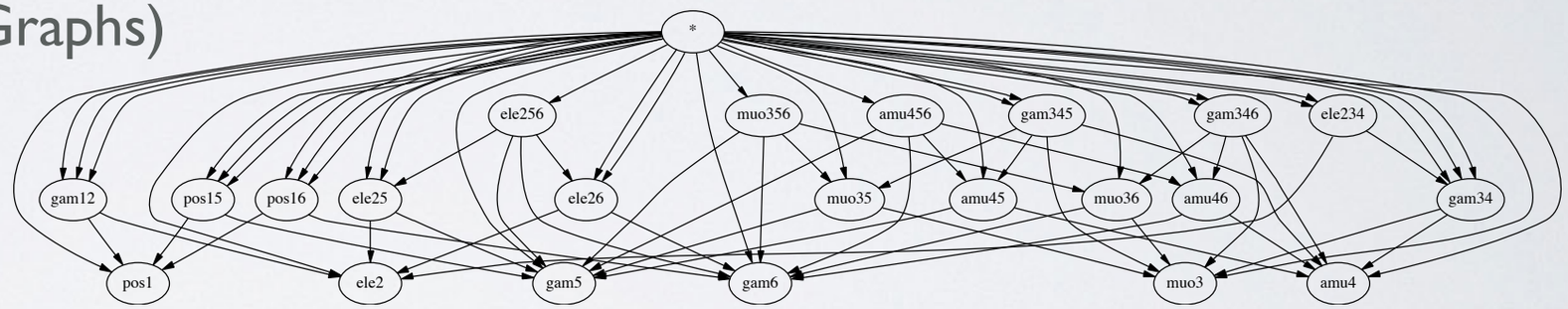
WHIZARD v2.2.6 (02.05.2015) *http://whizard.hepforge.org* <*whizard@desy.de*>

WHIZARD Team: *Wolfgang Kilian, Thorsten Ohl, JRR, Bijan Chokoufé/Marco Sekulla/Christian Weiss/Florian Staub* + *2 Master + 2 PhD (soon)*

EPJ C71 (2011) 1742

- Universal event generator for lepton and hadron colliders
- Modular package: - Phase space parameterization (resonances, collinear emission, Coulomb etc.)
  - O'Mega optimized matrix element generator (recursiveness via Directed Acyclical Graphs)





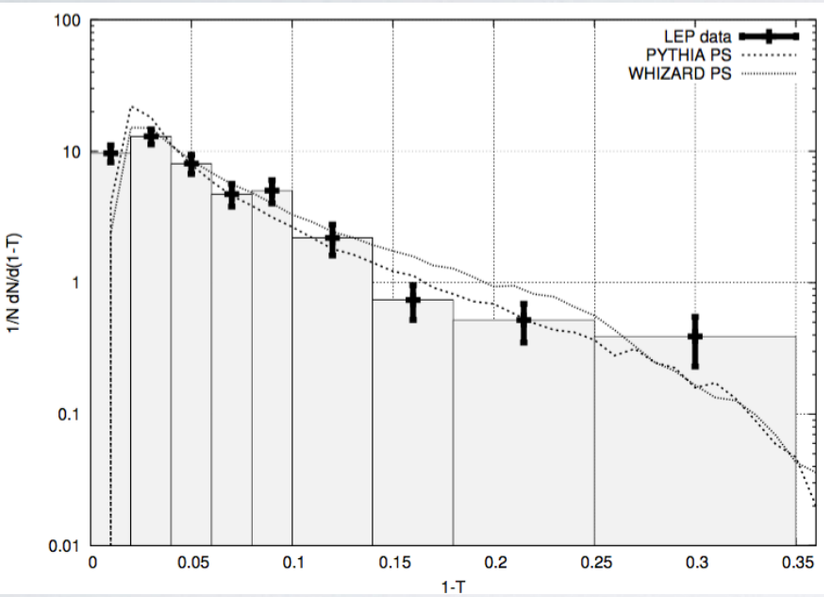
  - VAMP: adaptive multi-channel Monte Carlo integrator
  - CIRCE1/2: generator/simulation tool for lepton collider beam spectra
  - Lepton beam ISR Kuraev/Fadin, 2003; Skrzypek/Jadach, 1991
  - Color flow formalism Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Speckner, 2011

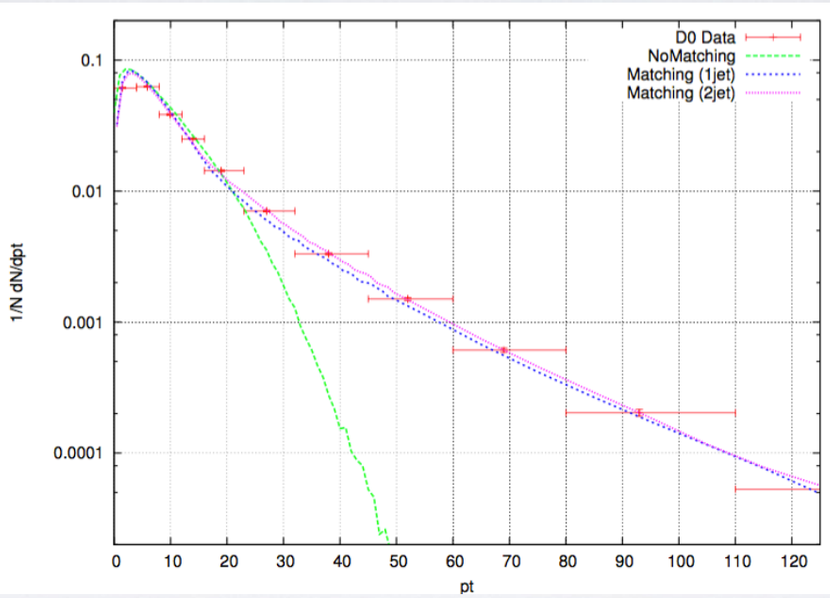
- Interfaces to external packages for Feynman rules, hadronization, tau decays, event formats, analysis, jet clustering etc. : `FastJet, GoSam, GuineaPig(++), HepMC, HOPPET, LCIO, LHAPDF(4/5/6), LoopTools, OpenLoops, PYTHIA6, [PYTHIA8], StdHep`

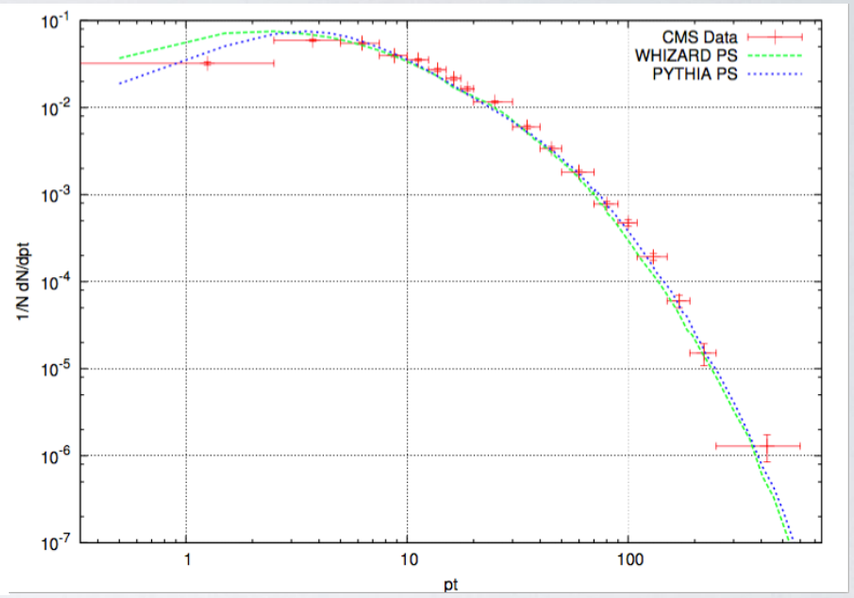
WHIZARD Parton Shower

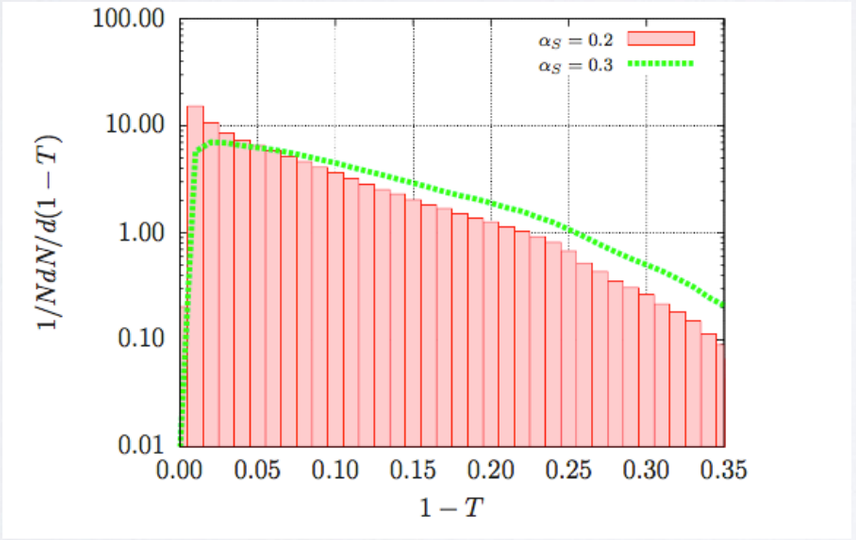
- Two independent implementations: kT-ordered QCD and Analytic QCD shower
- Analytic shower: no shower veto ⇒ exact shower history known, allows reweighting

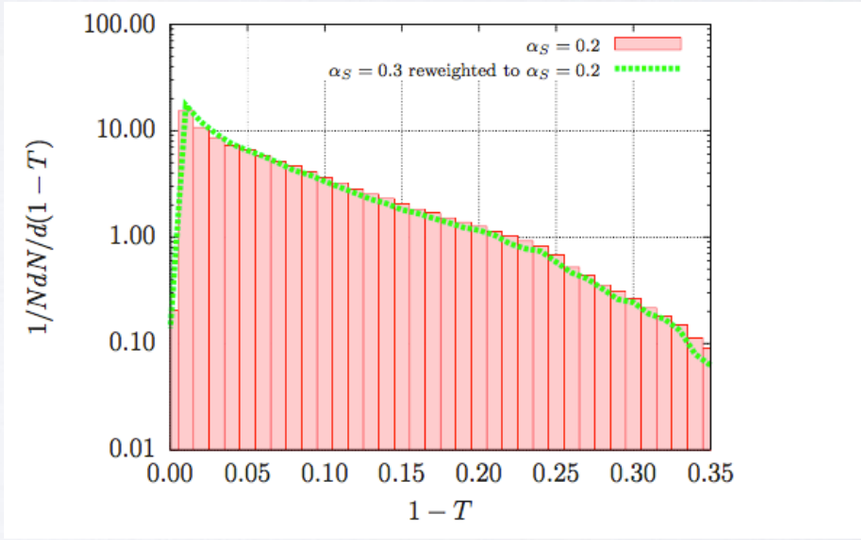
Kilian/JRR/Schmidt/Wiesler, JHEP **1204** 013 (2012)











- Technical overhaul of the shower / merging part
- Plans: implement GKS matching, QED shower (also interleaved, infrastructure ready)

2) Fixed-order NLO automation & POWHEG matching in WHIZARD

NLO Development in WHIZARD

- Need for precision predictions that match (sub-) percent experimental accuracy
- mainly NLO corrections, but also QED and electroweak (ee)

Binoth Les Houches Interface (BLHA): Workflow

1. Process definition in SINDARIN (contract to One-Loop Program [OLP])
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(first focus on QCD corrections)

- ★ `GoSam` [G. Cullen et al.] (Talk by G. Ossola)
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WHIZARD v2.2.6 contains alpha version

QCD corrections (massless and massive emitters)

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process eett = e1,E1 => t, tbar
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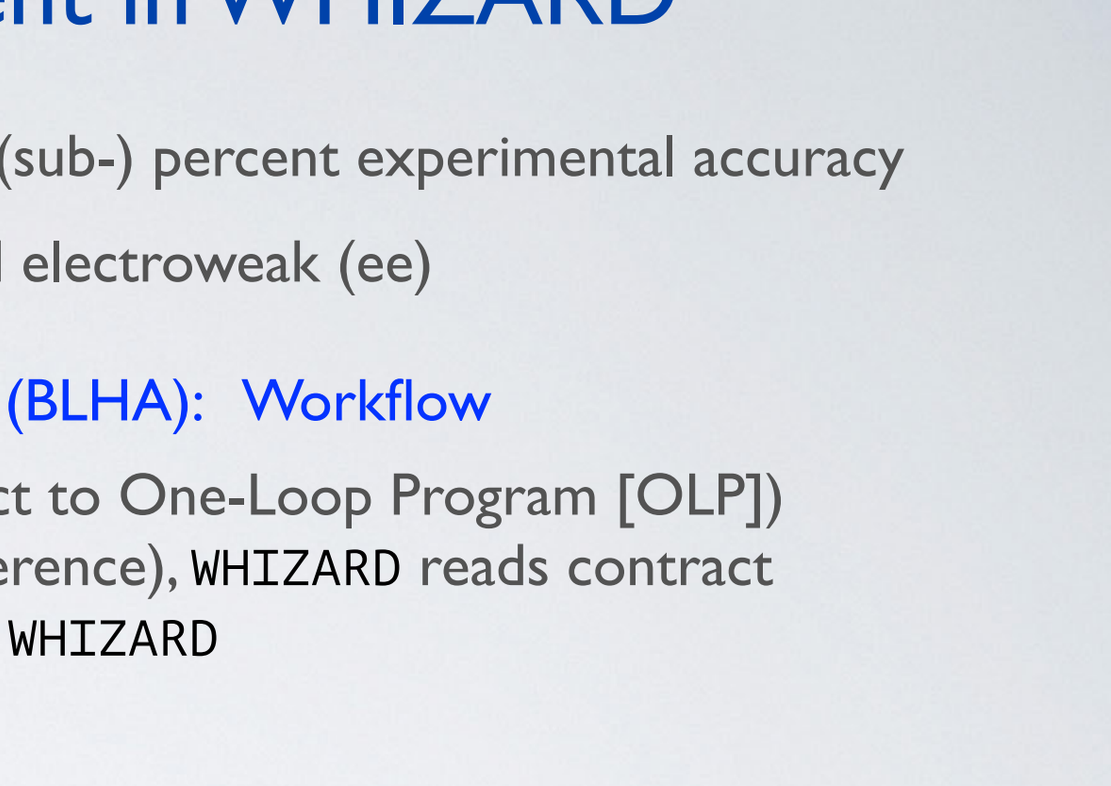

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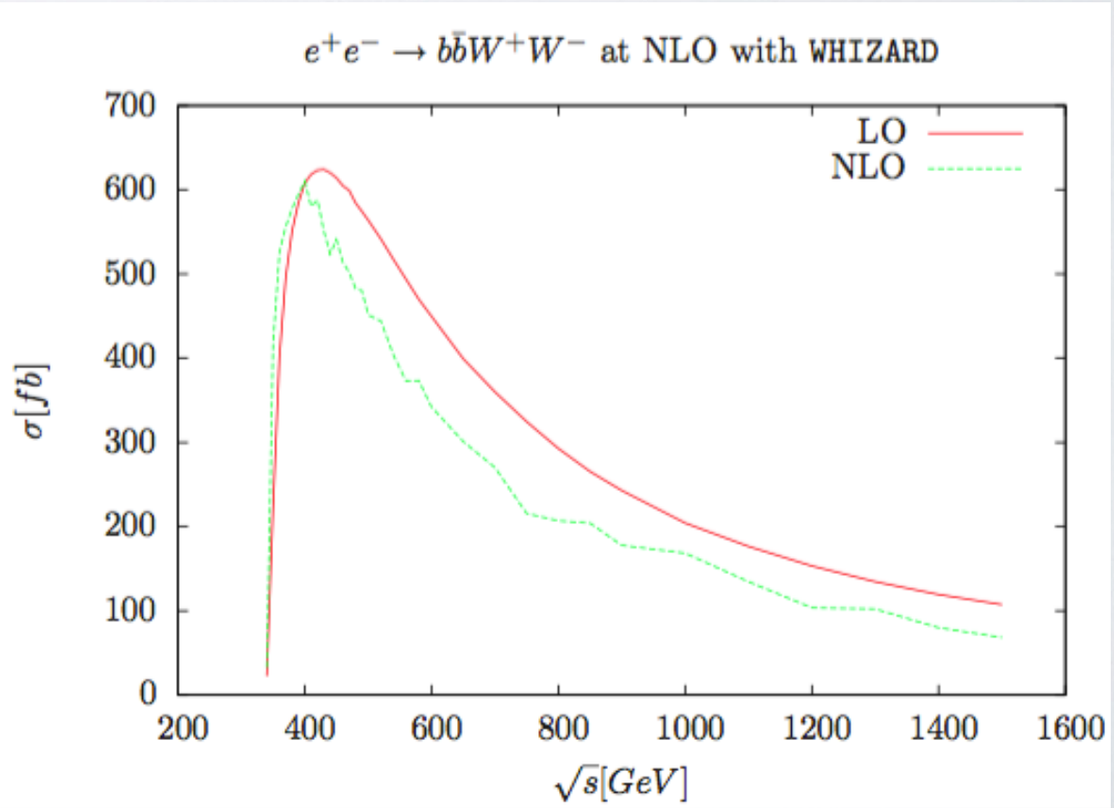

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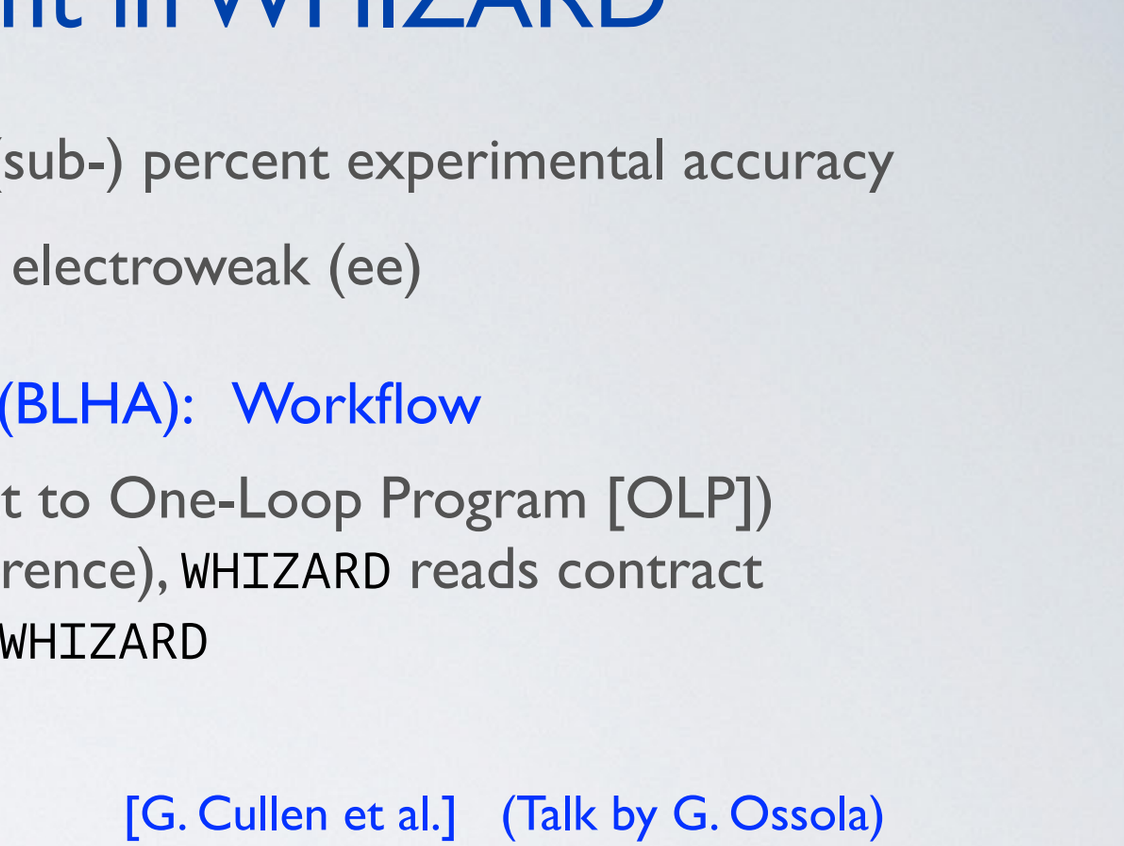

FKS Subtraction (Frixione/Kunszt/Signer)

Subtraction formalism to make real and virtual contributions separately finite

$$d\sigma^{\mathrm{NLO}} = \underbrace{\int_{n+1} \left(d\sigma^R - d\sigma^S\right)}_{\text{finite}} + \underbrace{\int_{n+1} d\sigma^S + \int_n d\sigma^V}_{\text{finite}}$$

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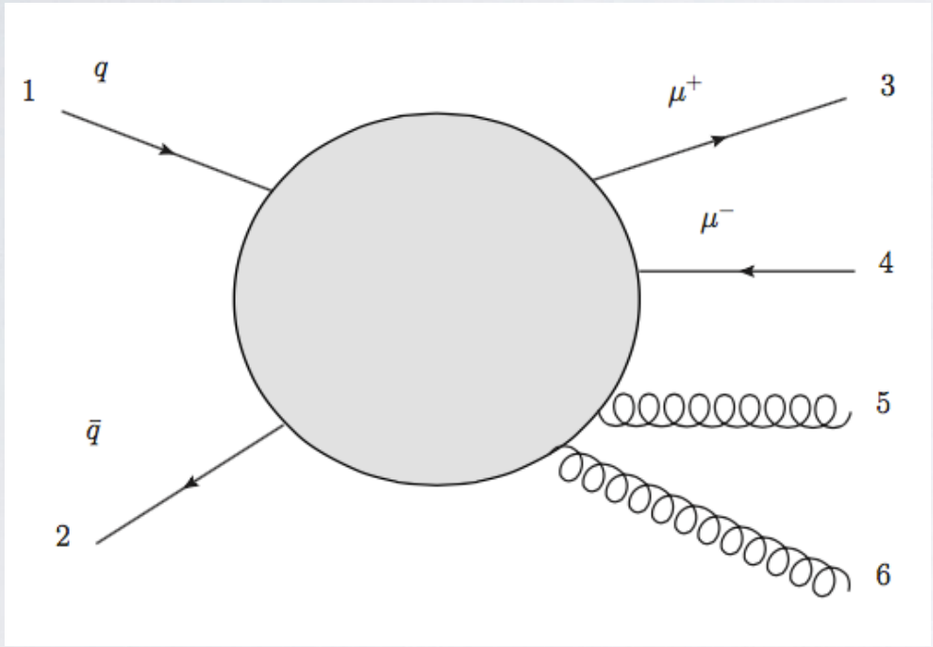

Automated subtraction terms in WHIZARD, algorithm:

- Find all singular pairs

$$\mathcal{I} = \{(1,5),(1,6),(2,5),(2,6),(5,6)\}$$

- Partition phase space according to singular regions

$$\mathbb{1} = \sum_{\alpha\in\mathcal{I}} S_\alpha(\Phi)$$

- Generate subtraction terms for singular regions

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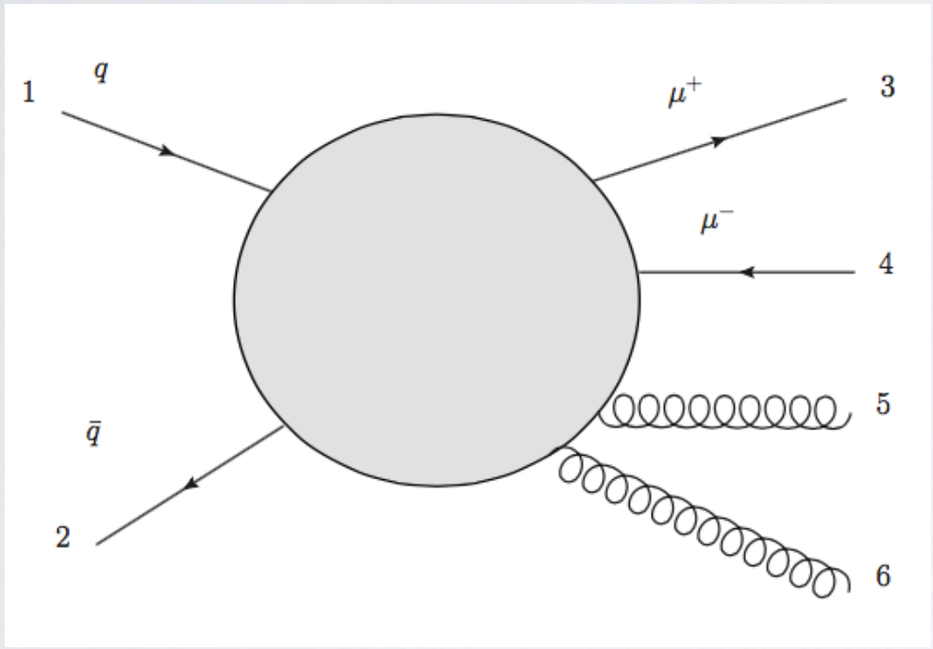

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Soft subtraction involves color-correlated matrix elements:

$$\mathcal{B}_{kl} \sim -\sum_{\substack{\text{color}\\ \text{spin}}} \mathcal{A}^{(n)}\vec{\mathcal{Q}}(\mathcal{I}_k)\cdot\vec{\mathcal{Q}}(\mathcal{I}_l)\mathcal{A}^{(n)*},$$

Collinear subtraction involves spin-correlated matrix elements:

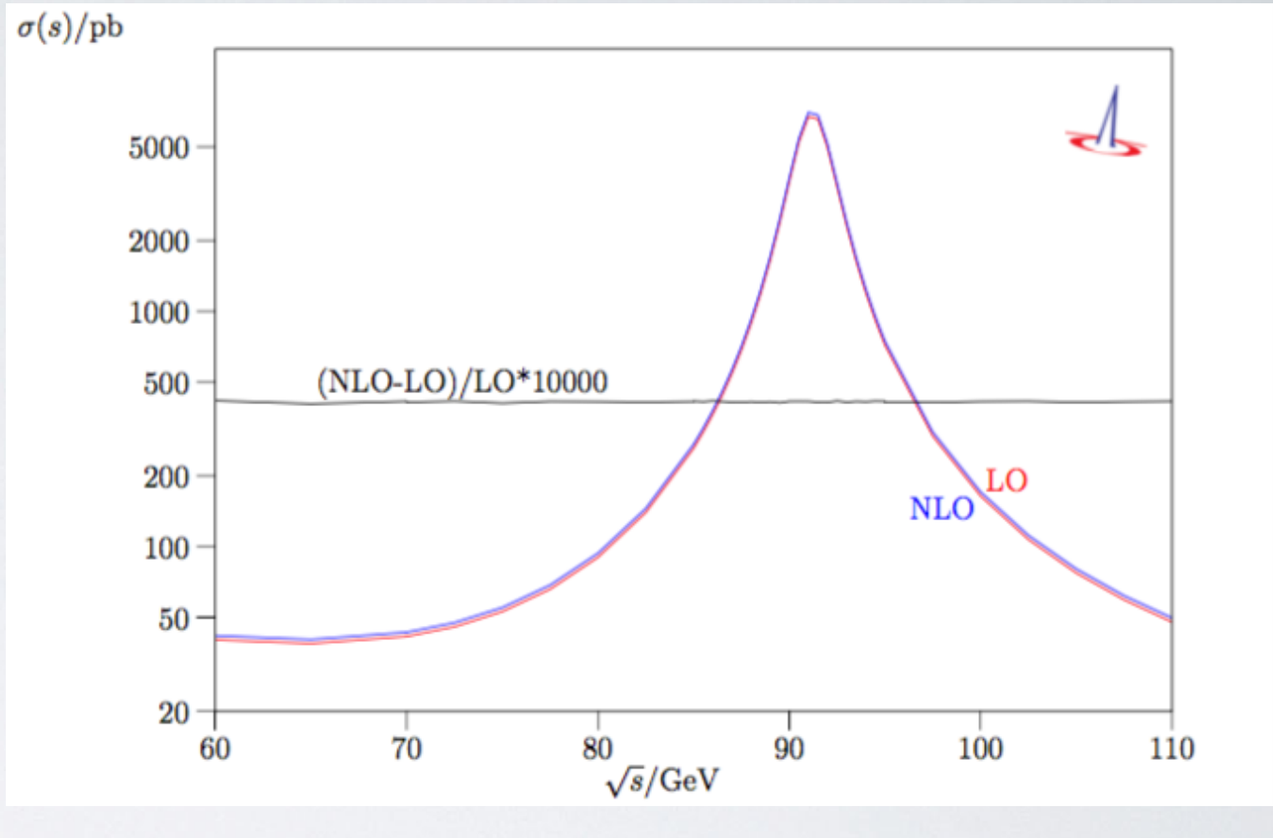
$$\mathcal{B}_{+-} \sim Re\left\{\frac{\langle k_{\mathrm{em}}k_{\mathrm{rad}}\rangle}{[k_{\mathrm{em}}k_{\mathrm{rad}}]}\sum_{\substack{\text{color}\\ \text{spin}}}\mathcal{A}_+^{(n)}\mathcal{A}_-^{(n)*}\right\}$$

Examples and Validation

Simplest benchmark process:

$$e^+e^- \to q\bar{q} \quad \text{with} \quad \left(\sigma^{\mathrm{NLO}} - \sigma^{\mathrm{LO}}\right)/\sigma^{\mathrm{LO}} = \alpha_s/\pi$$

Plot for total cross section for fixed strong coupling constant



List of validated QCD NLO processes

- $e^+e^- \to q\bar{q}$
- $e^+e^- \to q\bar{q}g$
- $e^+e^- \to \ell^+\ell^- q\bar{q}$
- $e^+e^- \to \ell^+\nu_\ell q\bar{q}$
- $e^+e^- \to t\bar{t}$
- $e^+e^- \to tW^-b$
- $e^+e^- \to W^+W^-b\bar{b}$
- $e^+e^- \to t\bar{t}H$

- Cross-checks with `MG5_aMC@NLO`
- Phase space integration for virtuals performs great

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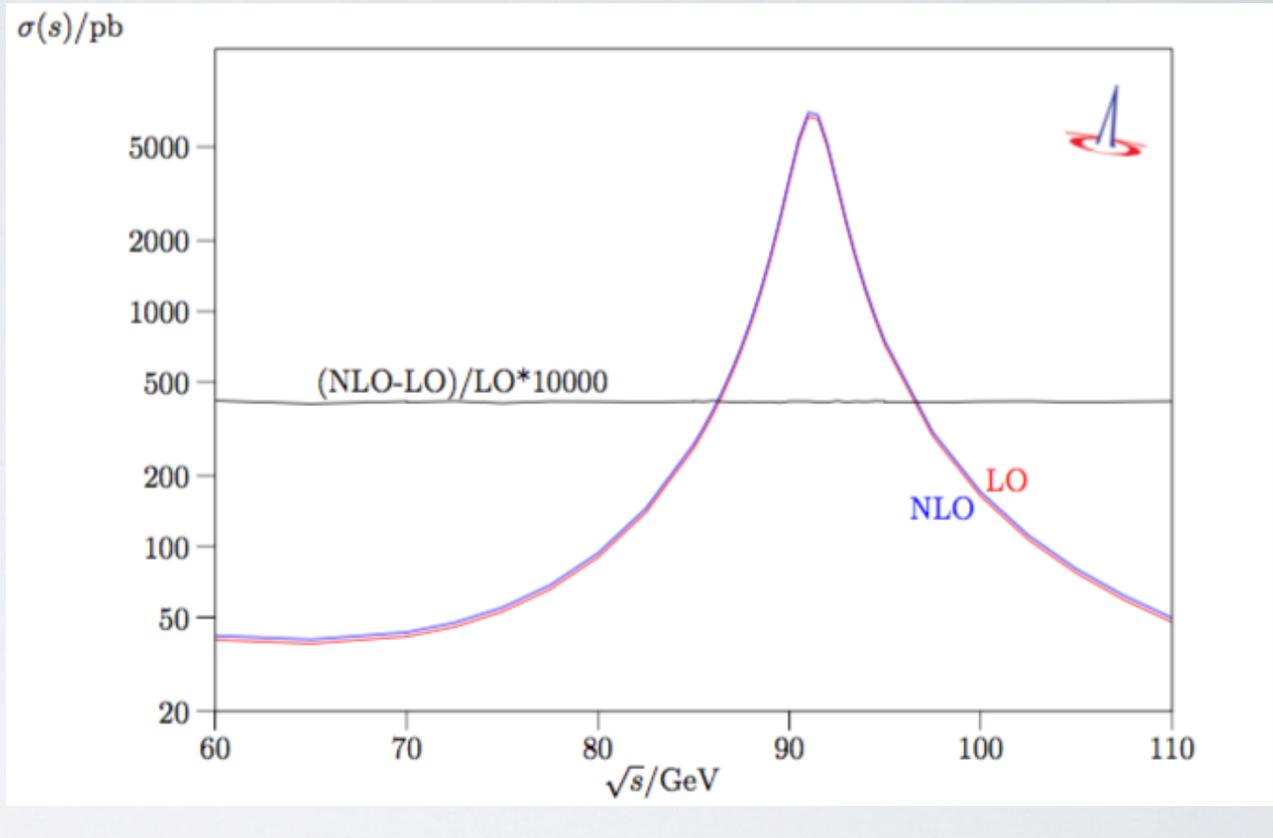

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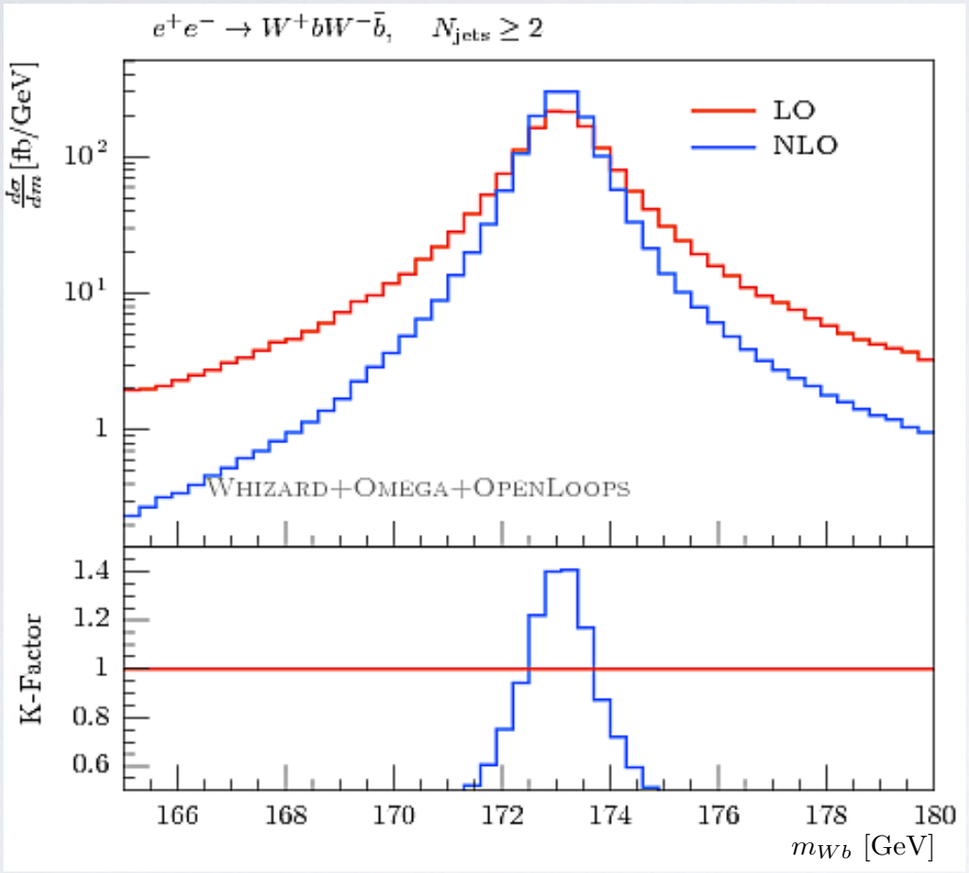
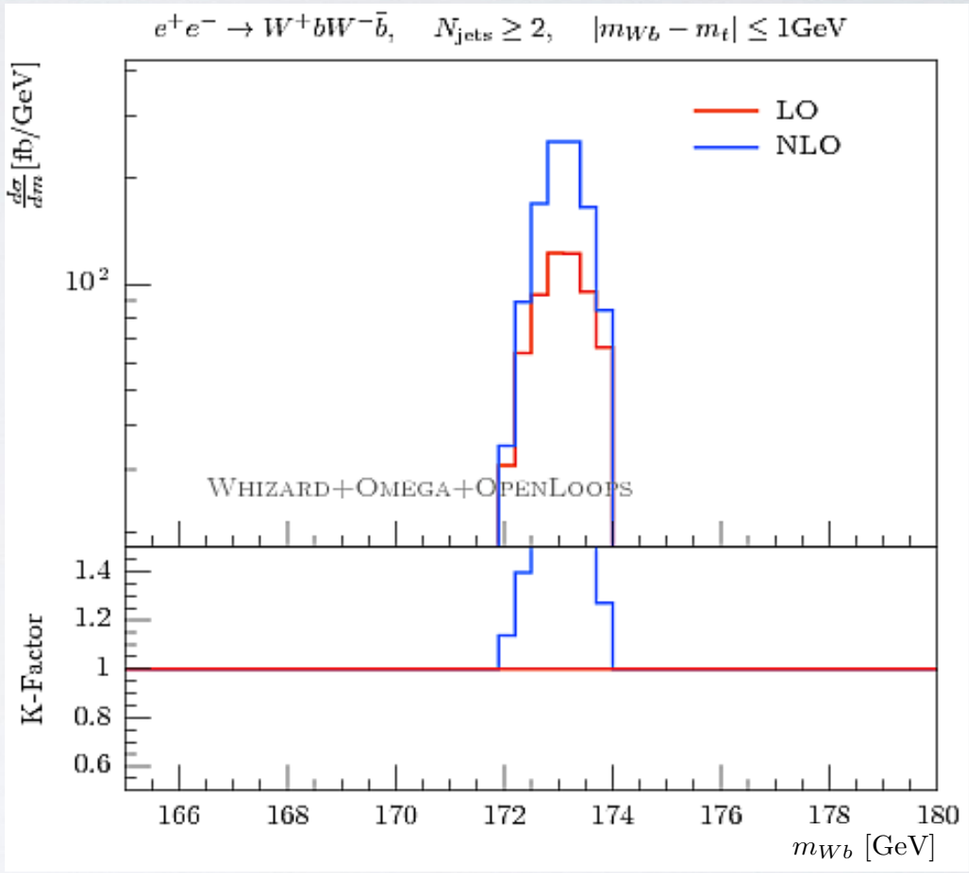
- ✦ QCD NLO infrastructure in pp almost complete
- ✦ First attempts on electroweak corrections, interfacing the RECOLA code [Denner et al.]

NLO Fixed-Order Events

- Add weights of real emission events to weight of Born kinematics using the FKS mapping
- Output weighted events in WHIZARD (e.g. using HepMC), then analysis with Rivet
- Example process: $e^+e^- \to W^+W^-b\bar{b}$





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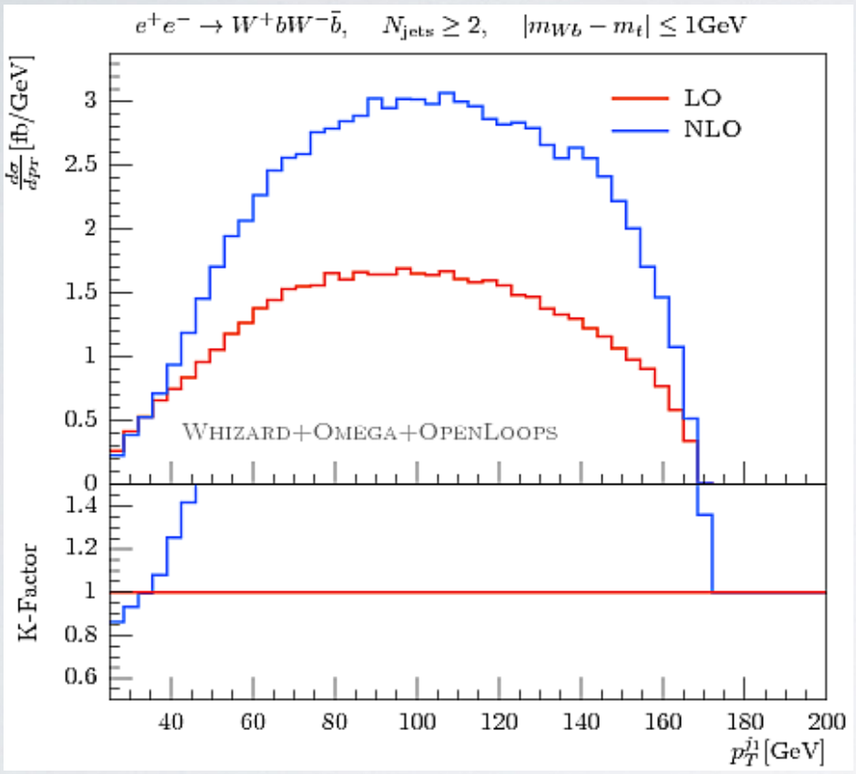

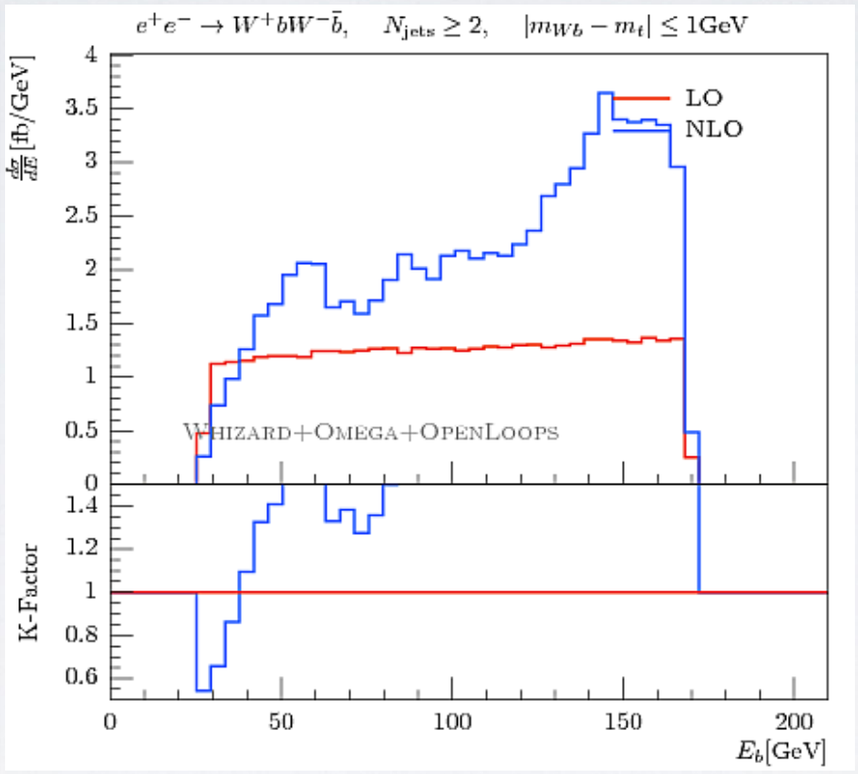

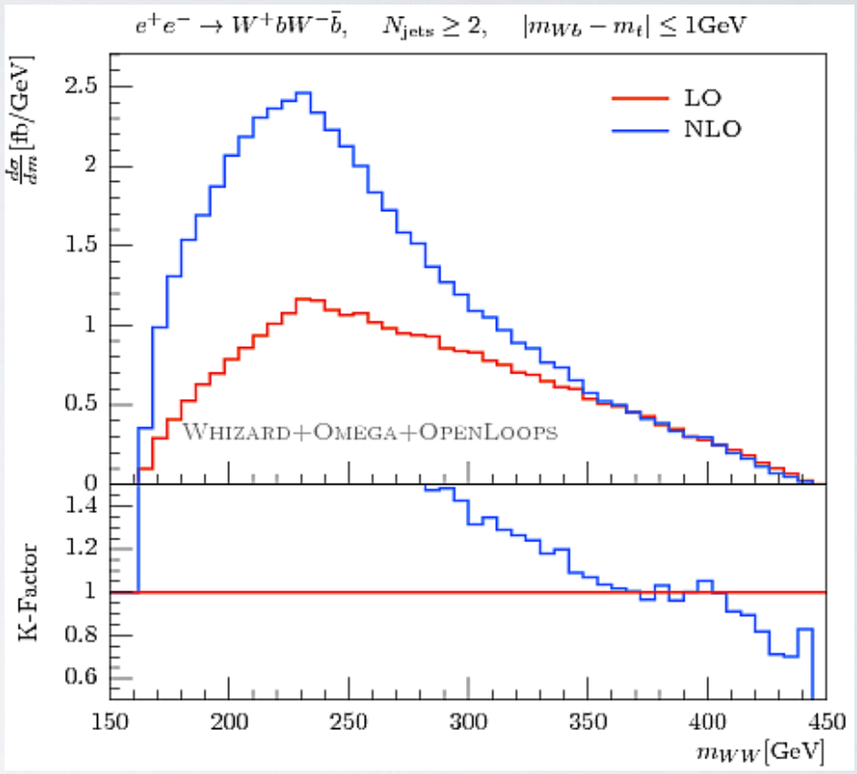

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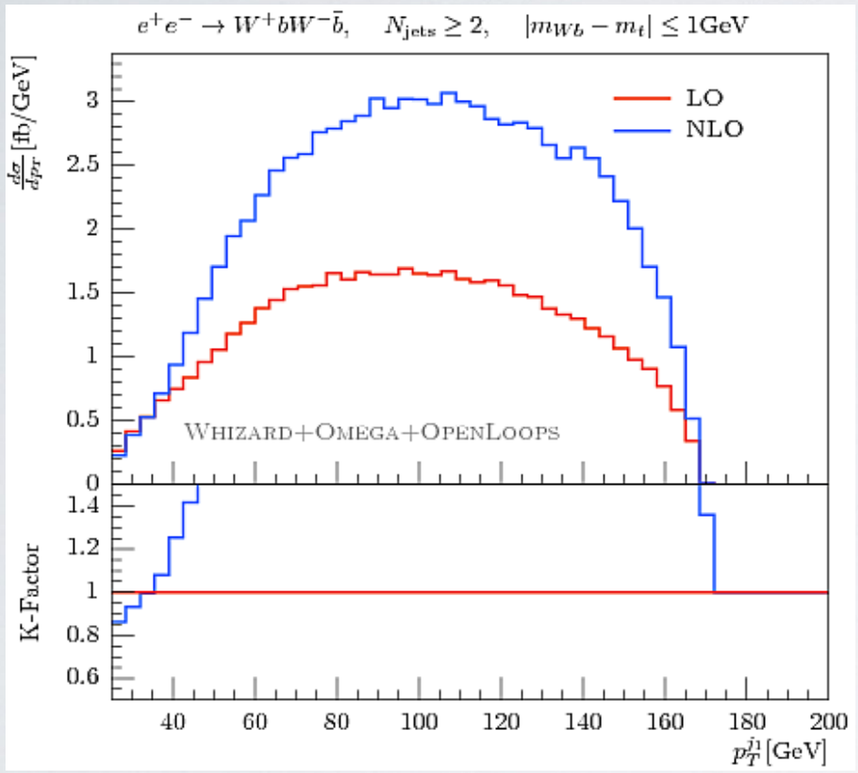
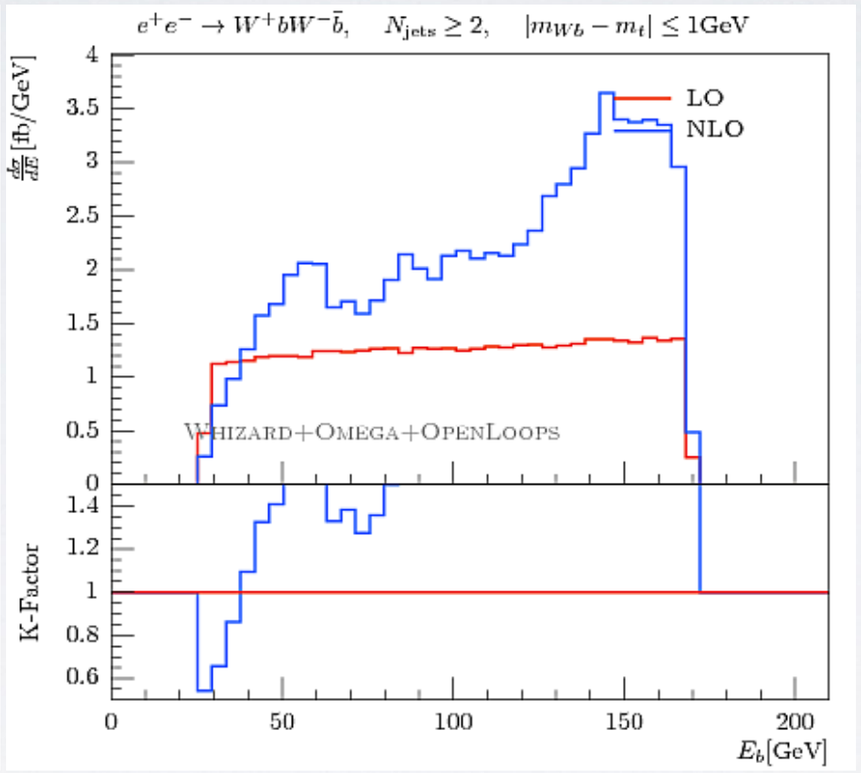
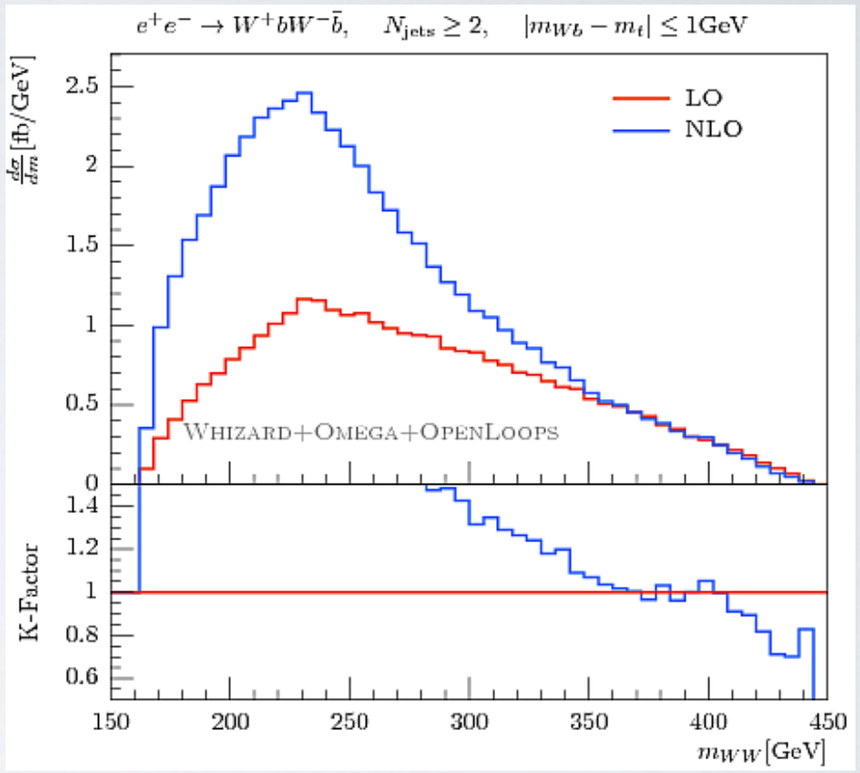


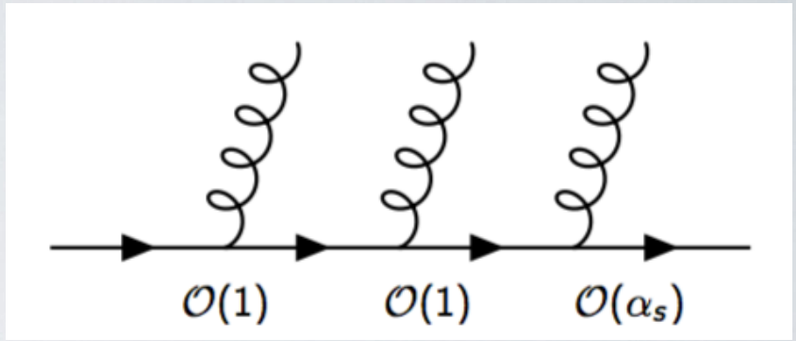




- Next steps: produce polarized results (remember: ILC will always run with polarization)
- Produce also plots including complete ISR photon radiation and beamstrahlung
- Investigate the full 2 → 6 process: e+e- → bbeμνν [Chokoufé/Lindert/JRR/Pozzorini/Weiss]

Automated POWHEG Matching in WHIZARD

- Soft gluon emissions before hard emission generate large logs
- Perturbative α_s : $|\mathcal{M}_{\text{soft}}|^2 \sim \frac{1}{k_T^2} \to \log \frac{k_T^{\max}}{k_T^{\min}}$
- Consistent matching of NLO matrix element with shower
- POWHEG method: hardest emission first [Nason et al.]



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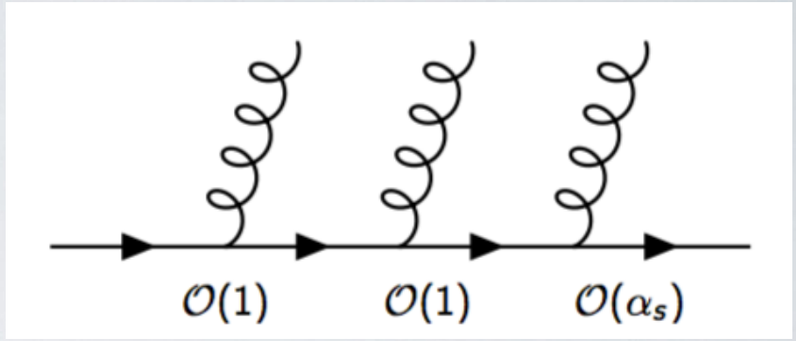

- Complete NLO events

$$\overline{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_{\rm rad} R(\Phi_{n+1})$$

- POWHEG generate events according to the formula:

$$d\sigma = \overline{B}(\Phi_n) \left[\Delta_R^{\rm NLO}(k_T^{\rm min}) + \Delta_R^{\rm NLO}(k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} d\Phi_{\rm rad} \right]$$

- Uses the modified Sudakov form factor:

$$\Delta_R^{\rm NLO}(k_T) = \exp\left[- \int d\Phi_{\rm rad} \frac{R(\Phi_{n+1})}{B(\Phi_n)} \theta(k_T(\Phi_{n+1}) - k_T) \right]$$

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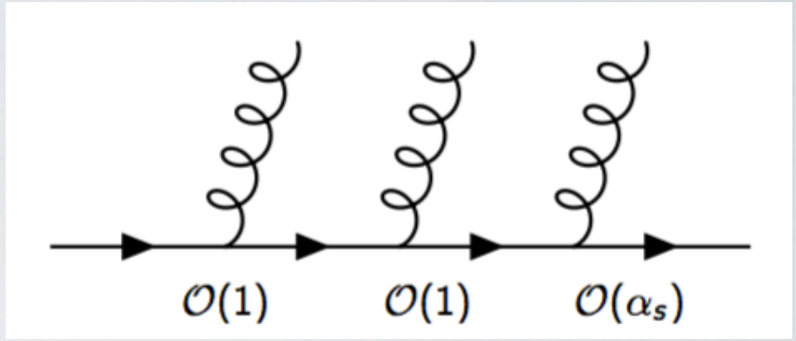

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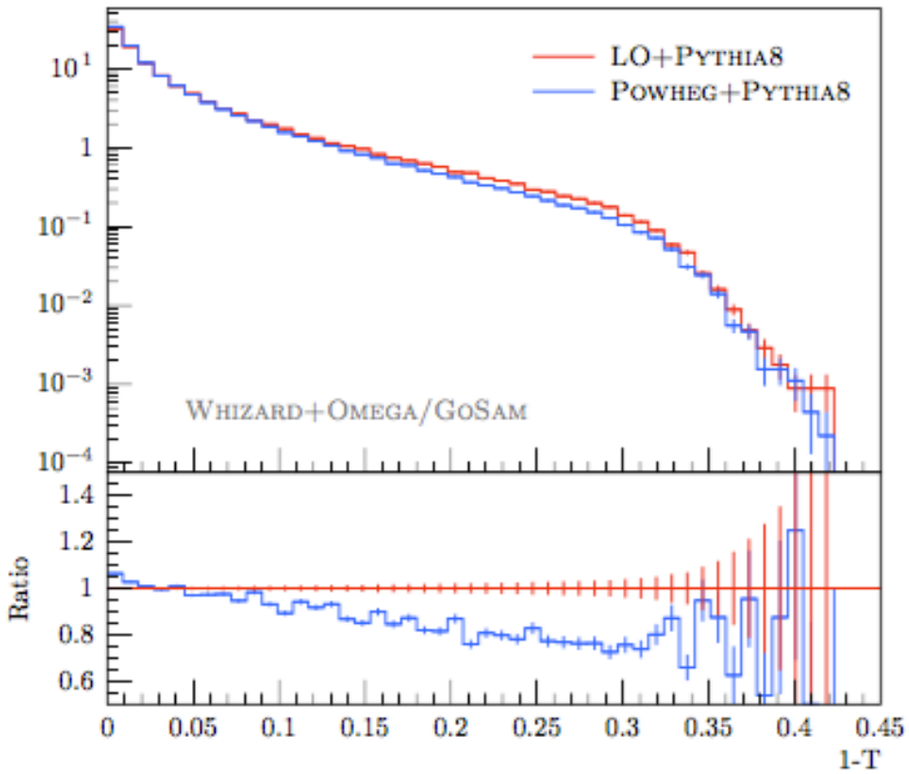
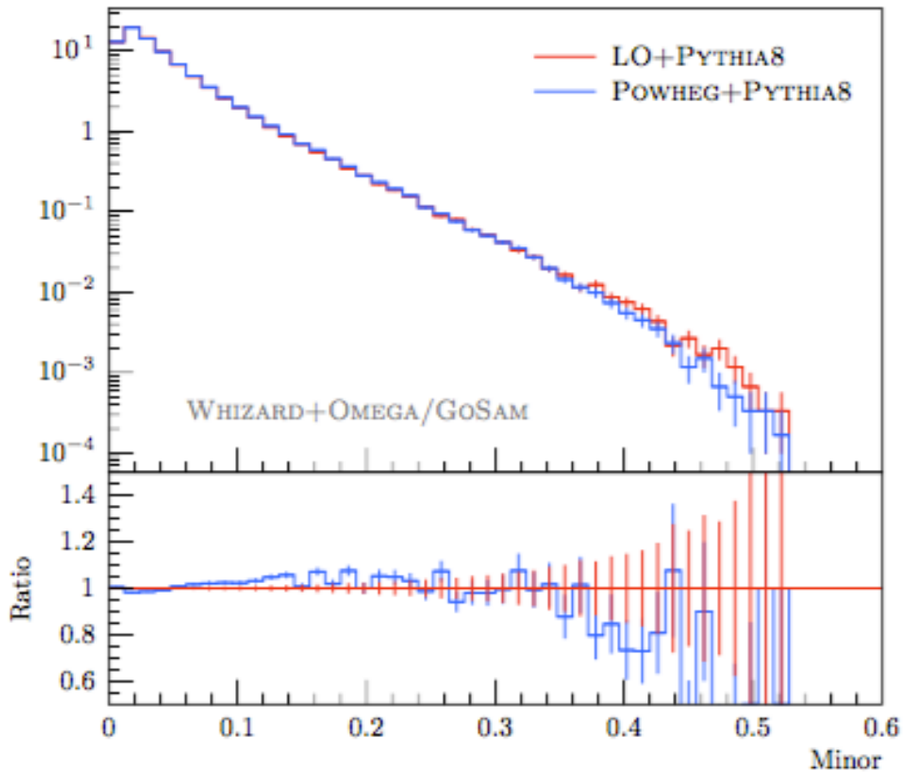
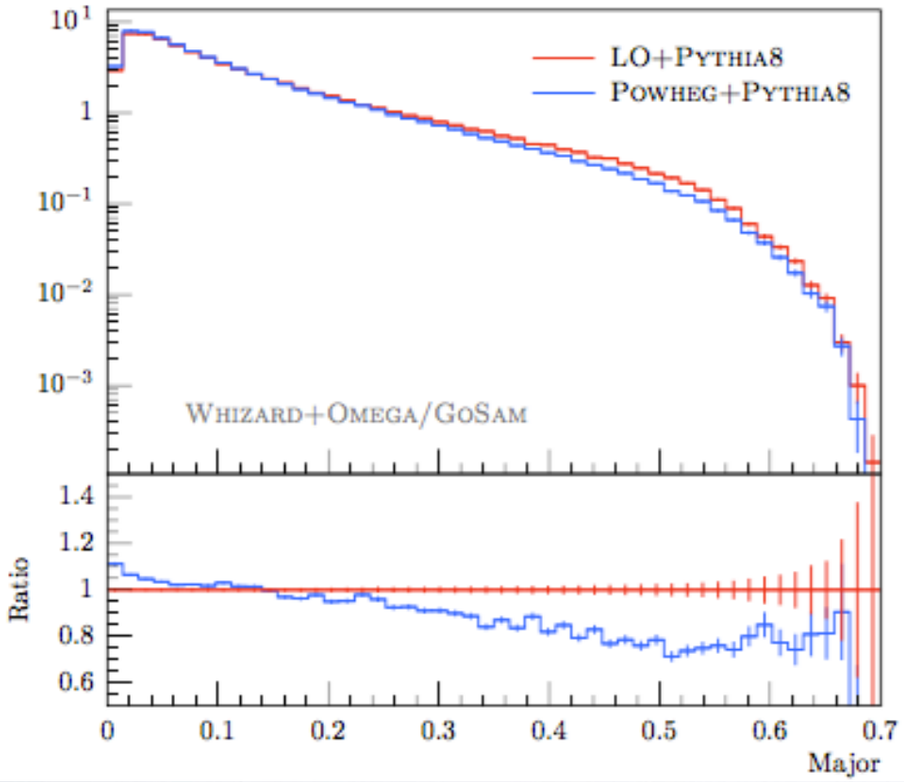
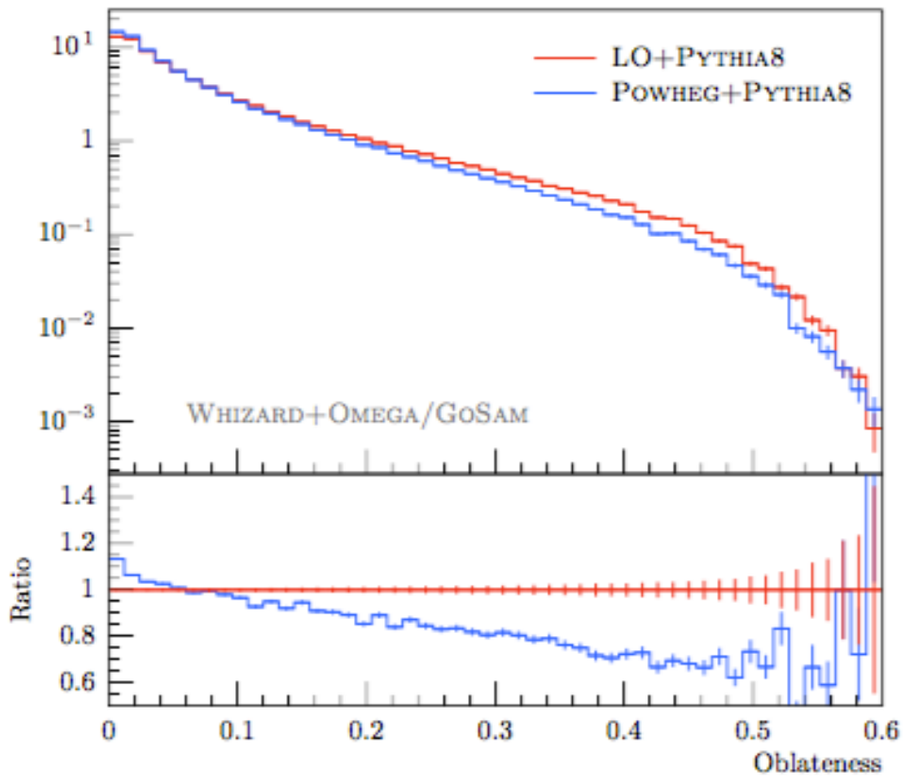
- Hardest emission: $k_T^{\rm max}$; shower with imposing a veto
- $\overline{B} < 0$ if virtual and real terms larger than Born: shouldn't happen in perturbative regions
- Reweighting such that $\overline{B} > 0$ for all events
- POWHEG: Positive Weight Hardest Emission Generator own implementation in WHIZARD

POWHEG Matching, example: e+e- to dijets







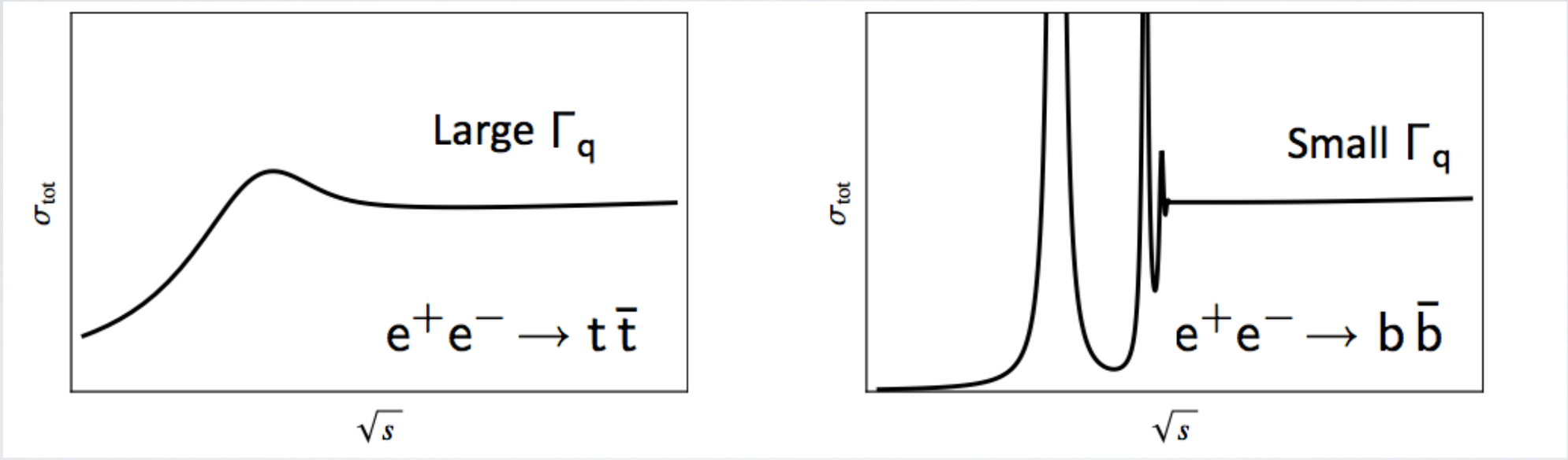


3) Top threshold in (N)LL (p)NRQCD matched to (N)LO QCD in WHIZARD

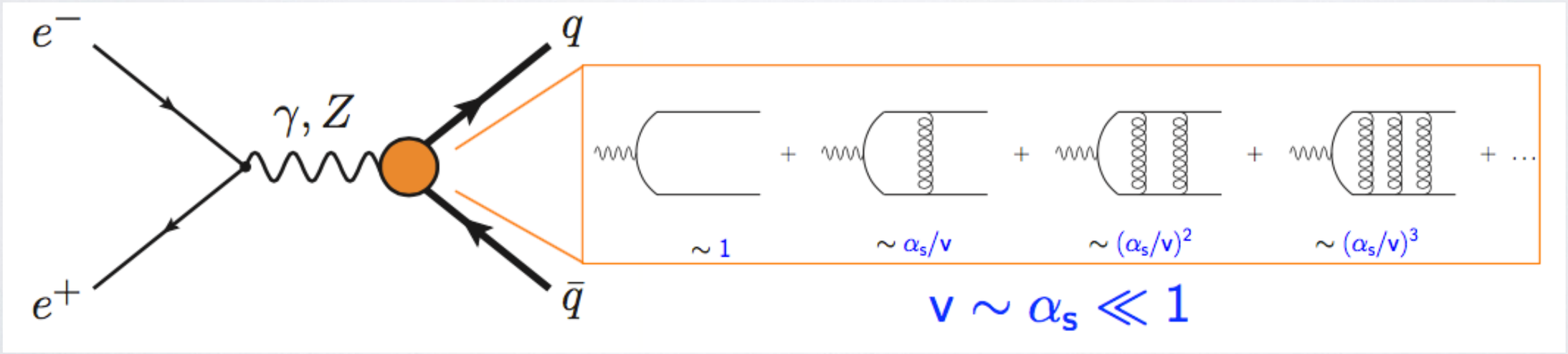
Top Threshold at lepton colliders

ILC top threshold scan best-known method to measure top quark mass, $\Delta M \sim 30\text{-}50$ MeV

Heavy quark production at lepton colliders, qualitatively:



Threshold region: top velocity $v \sim \alpha_s \ll 1$



Top Threshold Resummation in (p)NRQCD

- NRQCD is EFT for non-relativistic quark-antiquark systems: separate $M \cdot v$ and $M \cdot v^2$
- Integrate out hard quark and gluon d.o.f. (for more details: Talk by P. Marquardt)
- Resummation of singular terms close to threshold (v = 0) Hoang/Teubner, 1999; Hoang et al., 2001

Phase space of two massive particles

$$R \equiv \frac{\sigma_{t\bar{t}}}{\sigma_{\mu\mu}} = v \sum_k \left(\frac{\alpha_s}{v}\right)^k \sum_i (\alpha_s \ln v)^i \times$$

$$\times \left\{1\,(\mathrm{LL});\ \alpha_s, v\,(\mathrm{NLL});\ \alpha_s^2, \alpha_s v, v^2\,(\mathrm{NNLL})\right\}$$

(p/v)NRQCD EFT w/ RG improvement

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$$R^{\gamma,Z}(s) = \underbrace{F^v(s)R^v(s)}_{\text{s-wave: LL+NLL}} + \underbrace{F^a(s)R^a(s)}_{\text{p-wave}\sim v^2\text{:NNLL}}$$

but contributes
at NLL differentially!

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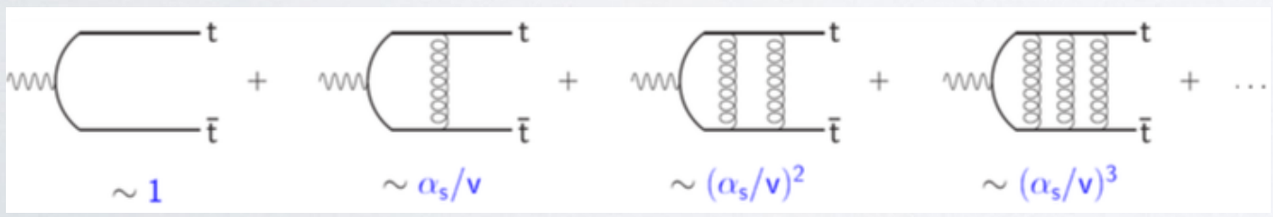
Coulomb potential gluon ladder resumption



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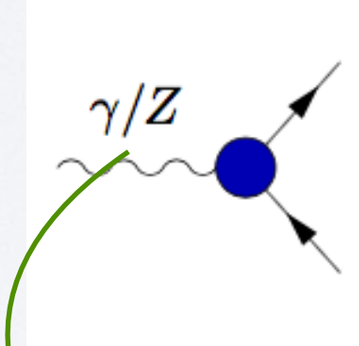
(p/v)NRQCD EFT w/ RG improvement

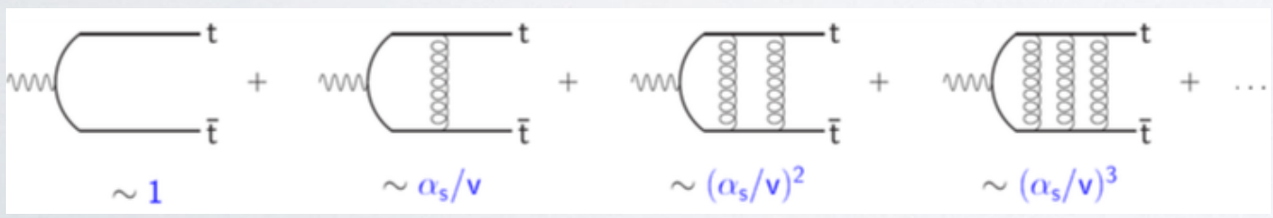
can be mapped onto effective *ttV* vertex



$$\sim \sqrt{R^{v/a}_{(\mathrm{N})\mathrm{LL}}} \sim \frac{\mathcal{G}^{v/a}_{(\mathrm{N})\mathrm{LL}}}{\mathcal{G}^{v/a}\big|_{\alpha_s=0}} \longrightarrow 1$$

far away from threshold

Coulomb potential gluon ladder resumption



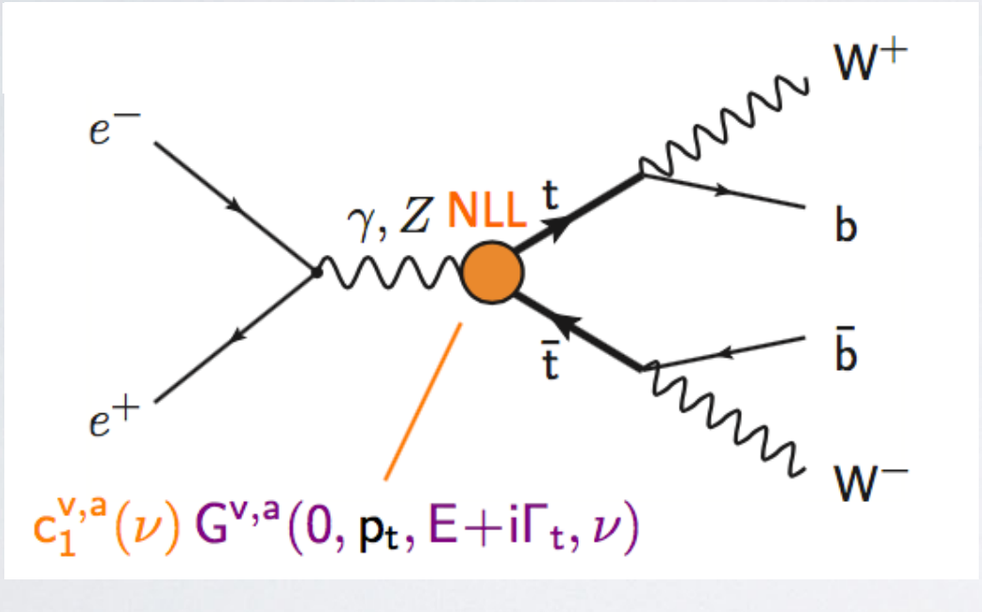
$$\mathbb{C} \ni \mathcal{G}^{v/a}_{(\mathrm{N})\mathrm{LL}} = \mathcal{G}^{v/a}_{(\mathrm{N})\mathrm{LL}}(\alpha_s, M_t^{\mathrm{pole}}, \sqrt{s}, |\vec{p}_t|, \Gamma_t)$$

differential in off-shell *tt* phase space

Top Threshold in WHIZARD

with F. Bach/A. Hoang/M. Stahlhofen

- Implement resummed threshold effects as effective vertex [form factor] in WHIZARD
- $G^{v,a}(0, p_t, E + i\Gamma_t, \nu)$ from TOPPIK code [Jezabek/Teubner], included in WHIZARD



- Default parameters:

$$\mathbf{M^{1S} = 172\,GeV},\ \Gamma_t = 1.54\,\mathrm{GeV},$$
$$\alpha_s(M_Z) = 0.118$$

$$M^{1S} = M_t^{pole}(1 - \Delta^{LL/NLL}_{(Coul.)})$$

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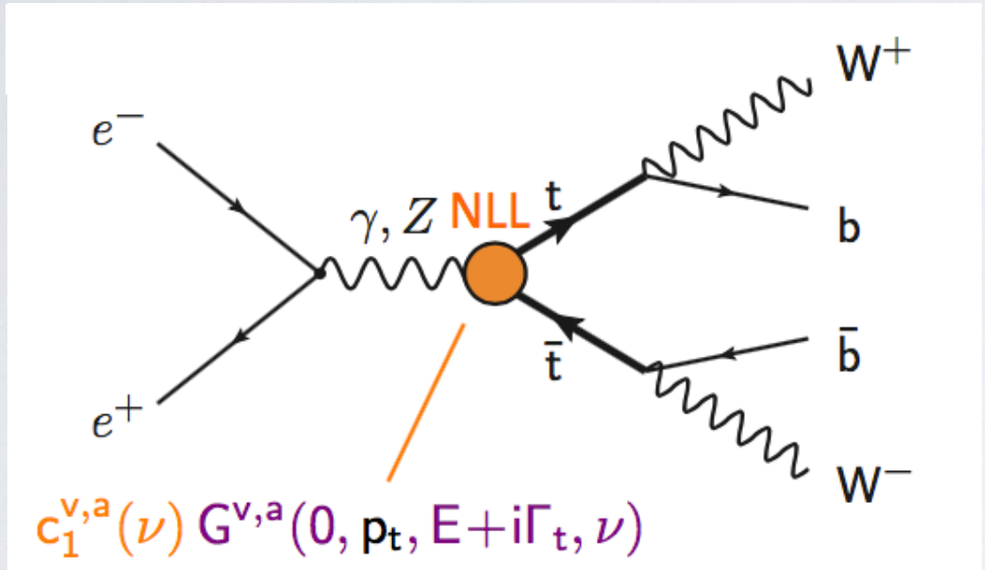

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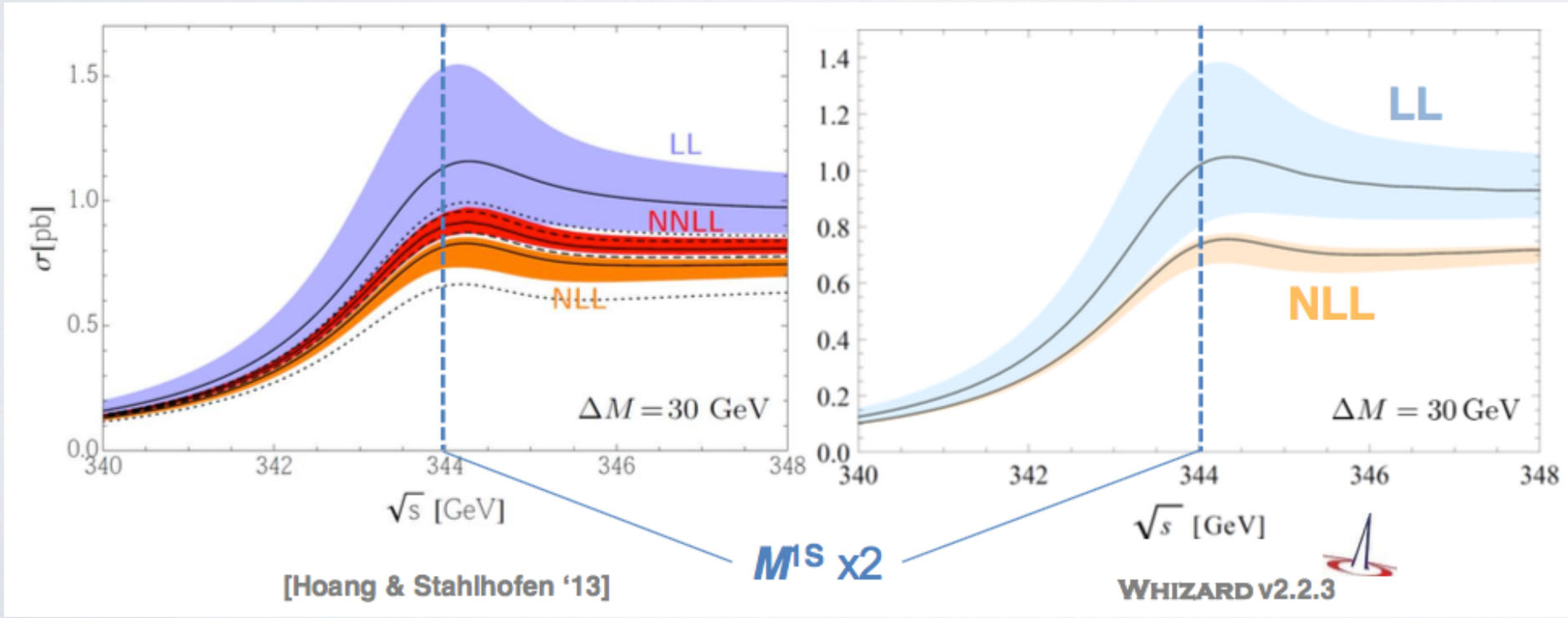

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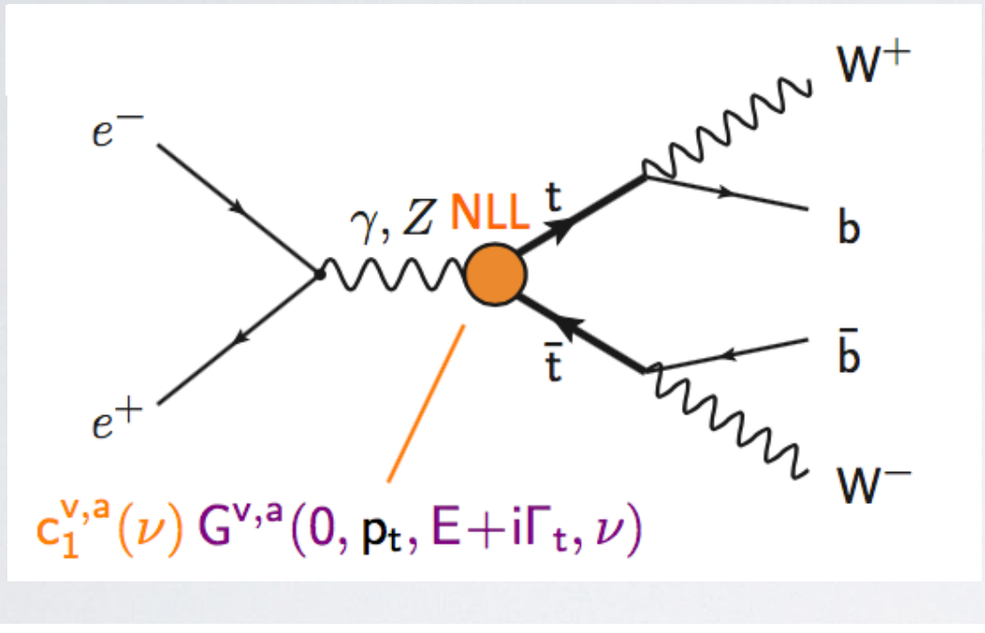

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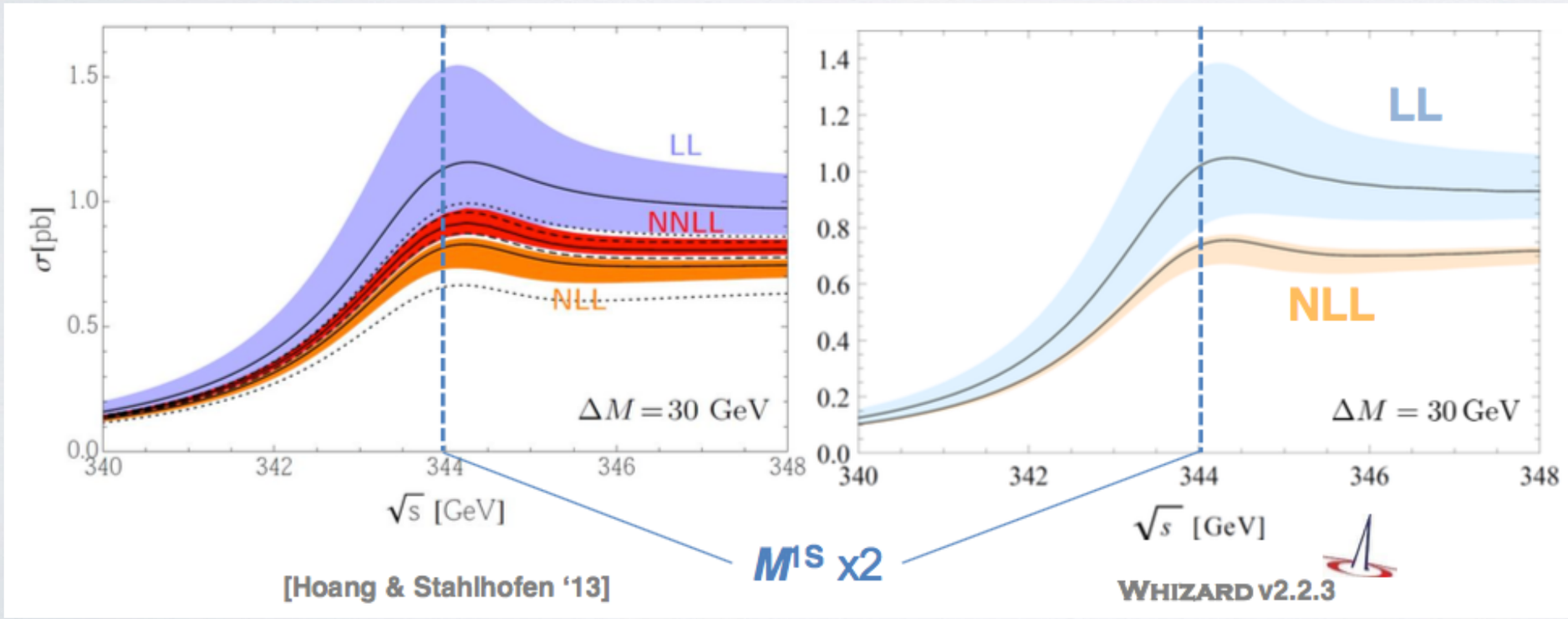
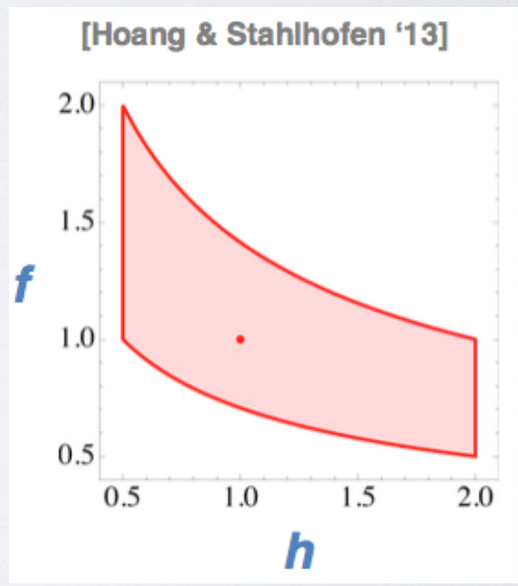
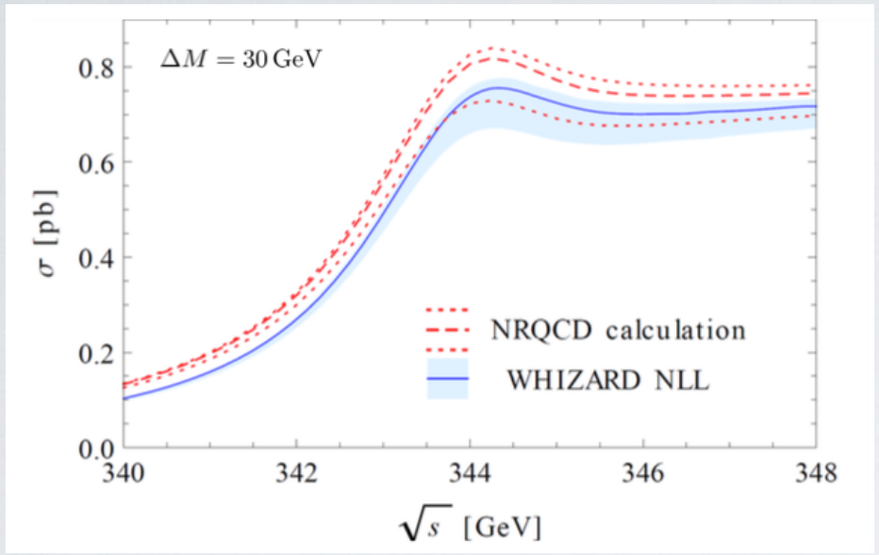
Theory uncertainties from scale variations:
hard and soft scale

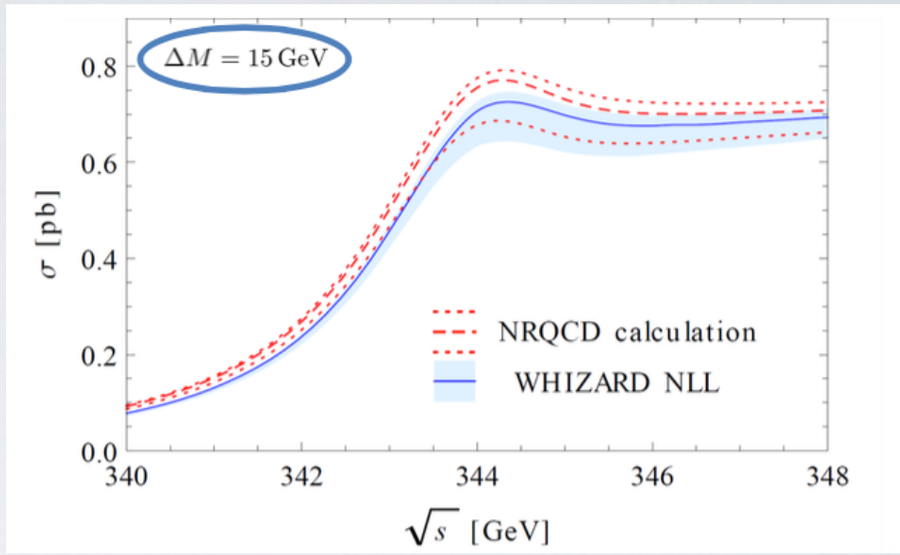
$$\mu_h = h \cdot m_t \qquad \mu_s = f \cdot m_t v$$





Sanity checks: correct limit for $\alpha_s \longrightarrow 0$, stable against variation of cutoff ΔM [15-30 GeV]





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  - Important effects: beamstrahlung; ISR; LO electroweak terms
  - More exclusive observables accessible

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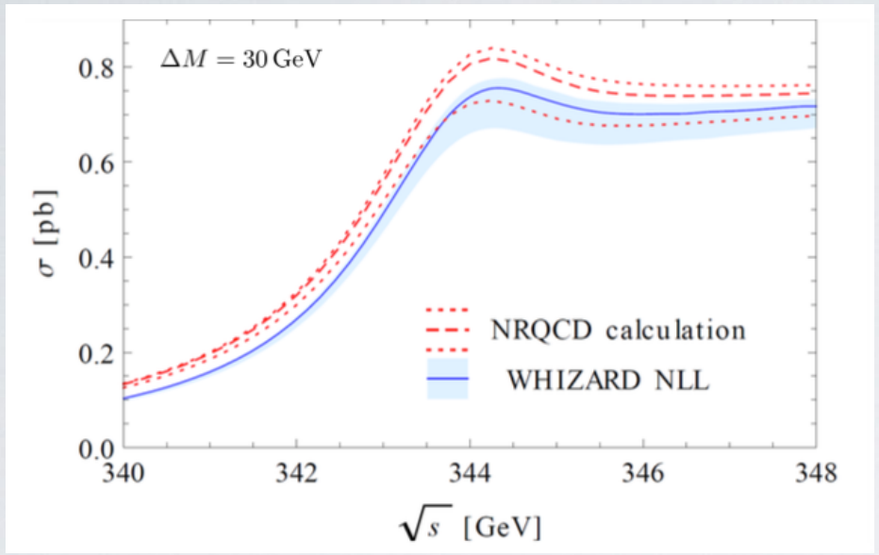

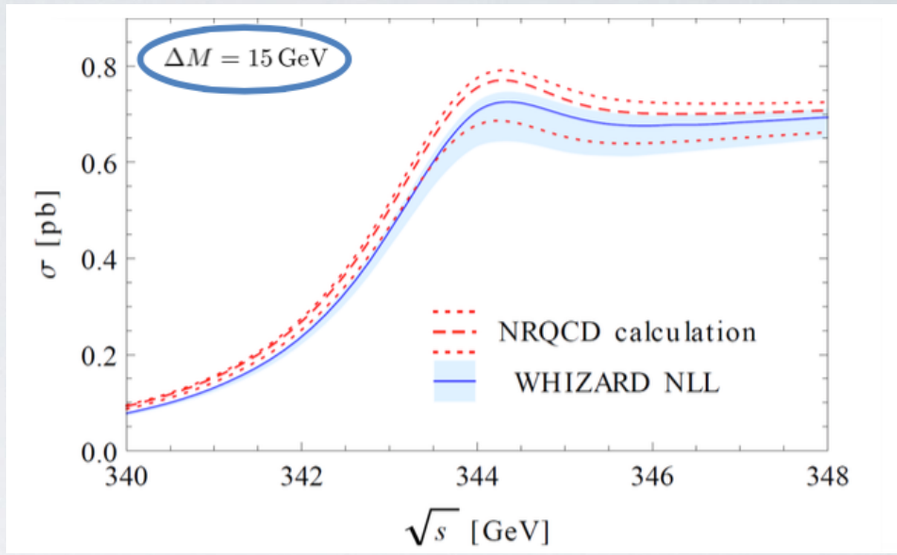

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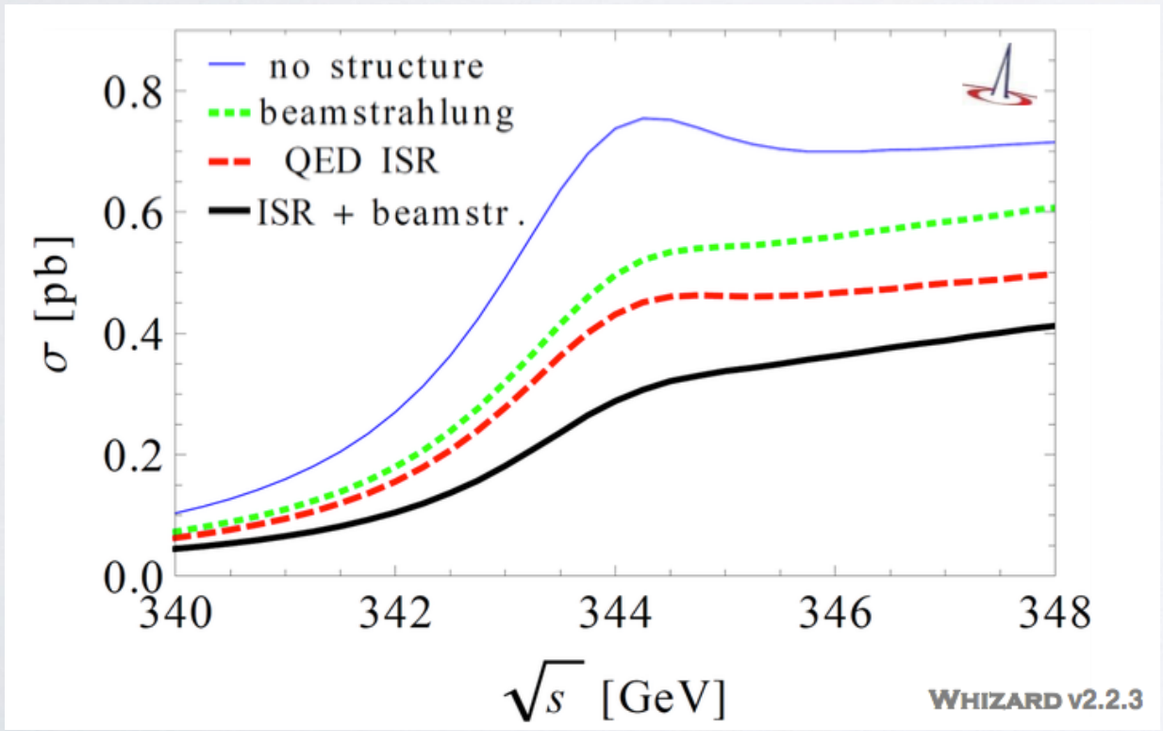

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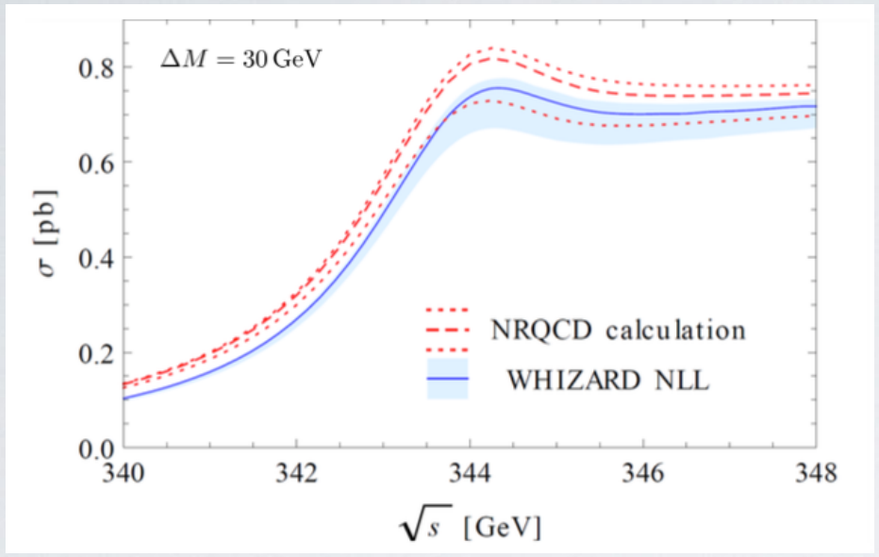

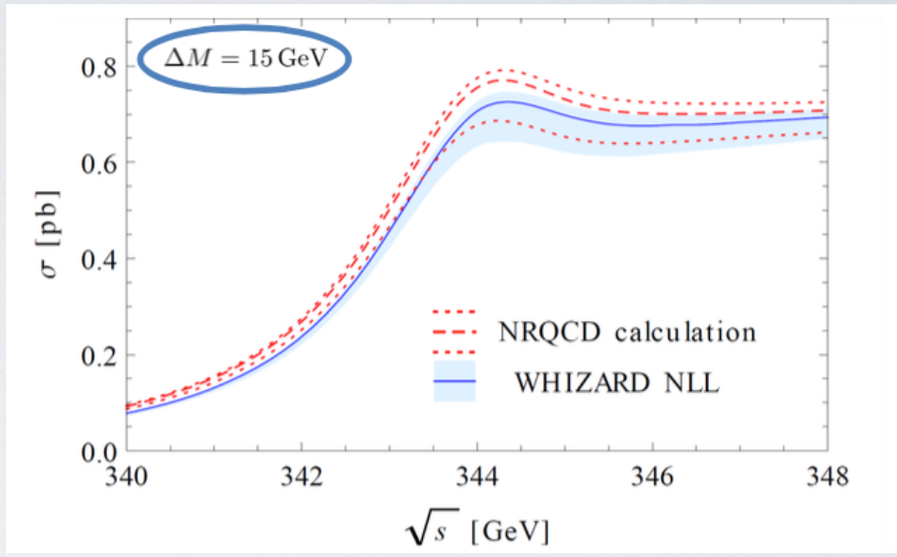

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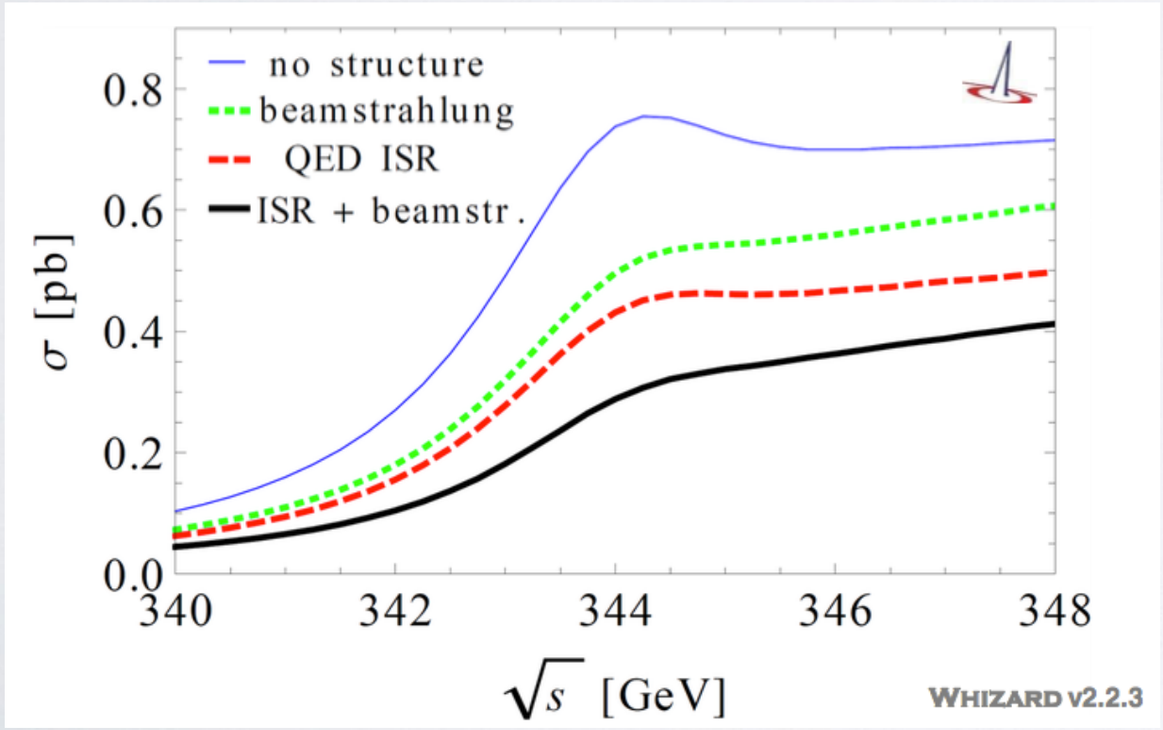
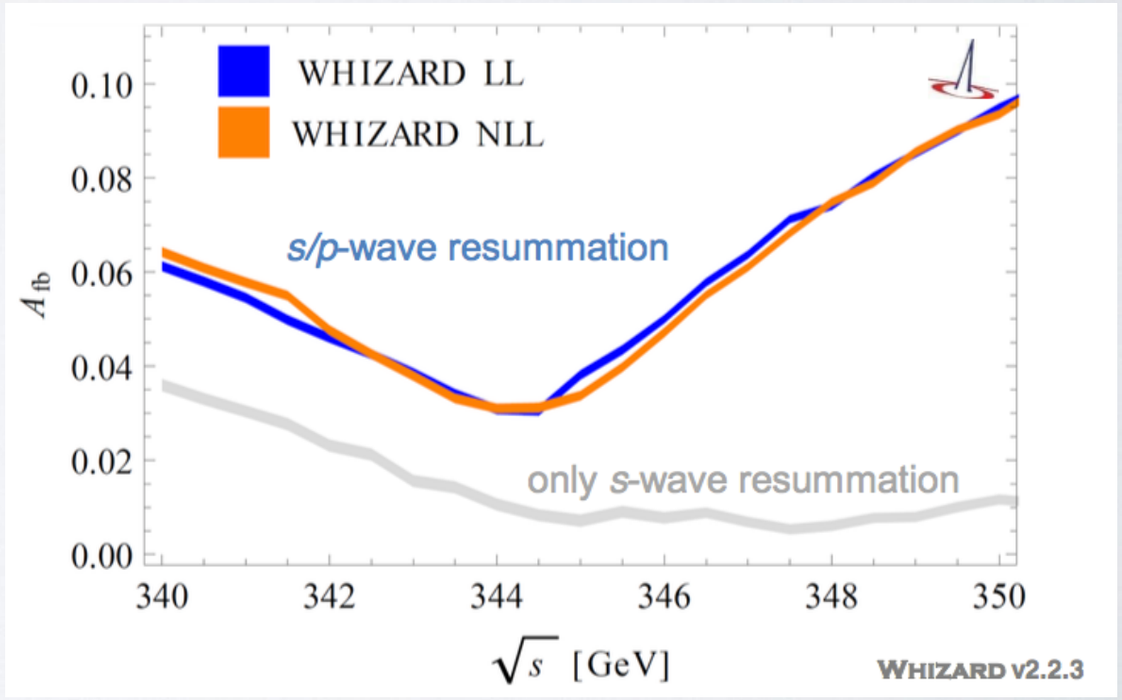
Forward-backward asymmetry (norm. ⇒ good shape stability)

$$A_{fb} := \frac{\sigma(p_z^t > 0) - \sigma(p_z^t) < 0)}{\sigma(p_z^t > 0) + \sigma(p_z^t < 0)}$$





Matching to continuum at LO and NLO

- Transition region between relativistic and resummation effects
- CLIC benchmark energies:

  0.38 TeV, 1.4 TeV, 3.0 TeV

Comparison of different approximations

- Leading order approximation
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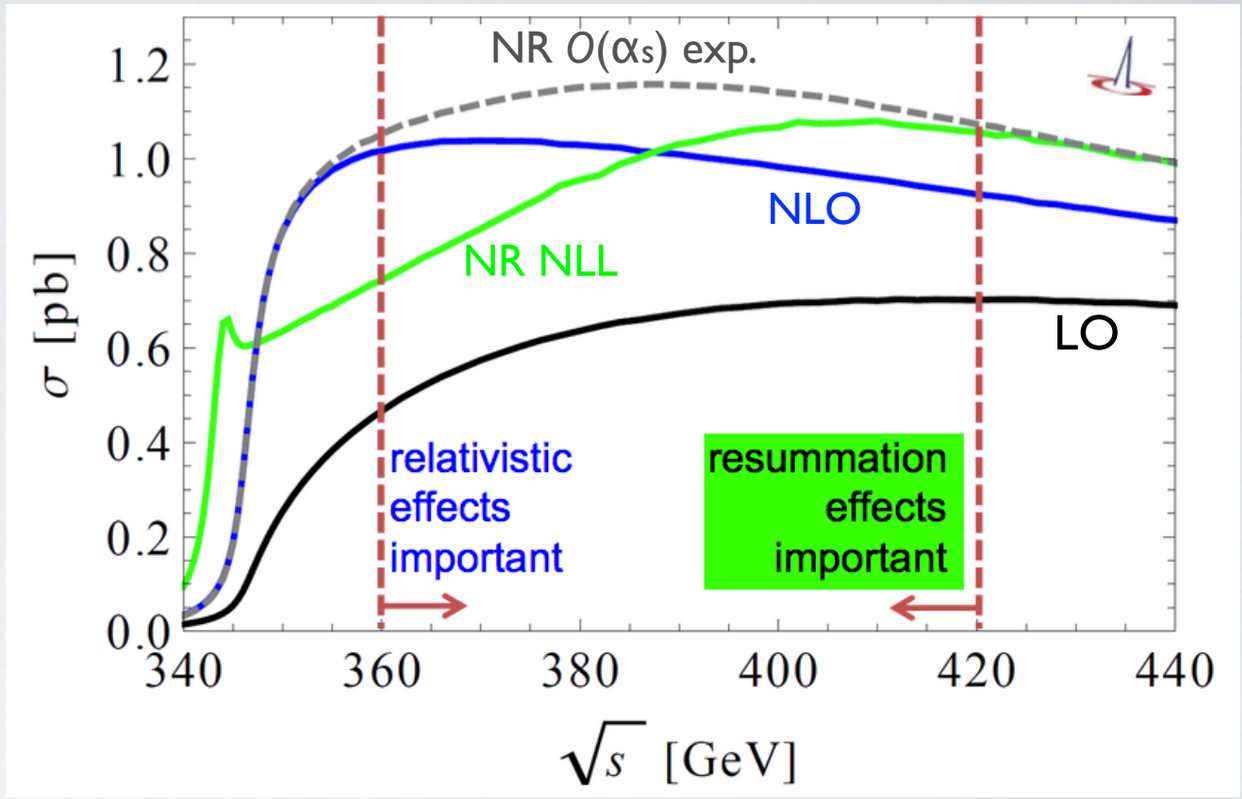
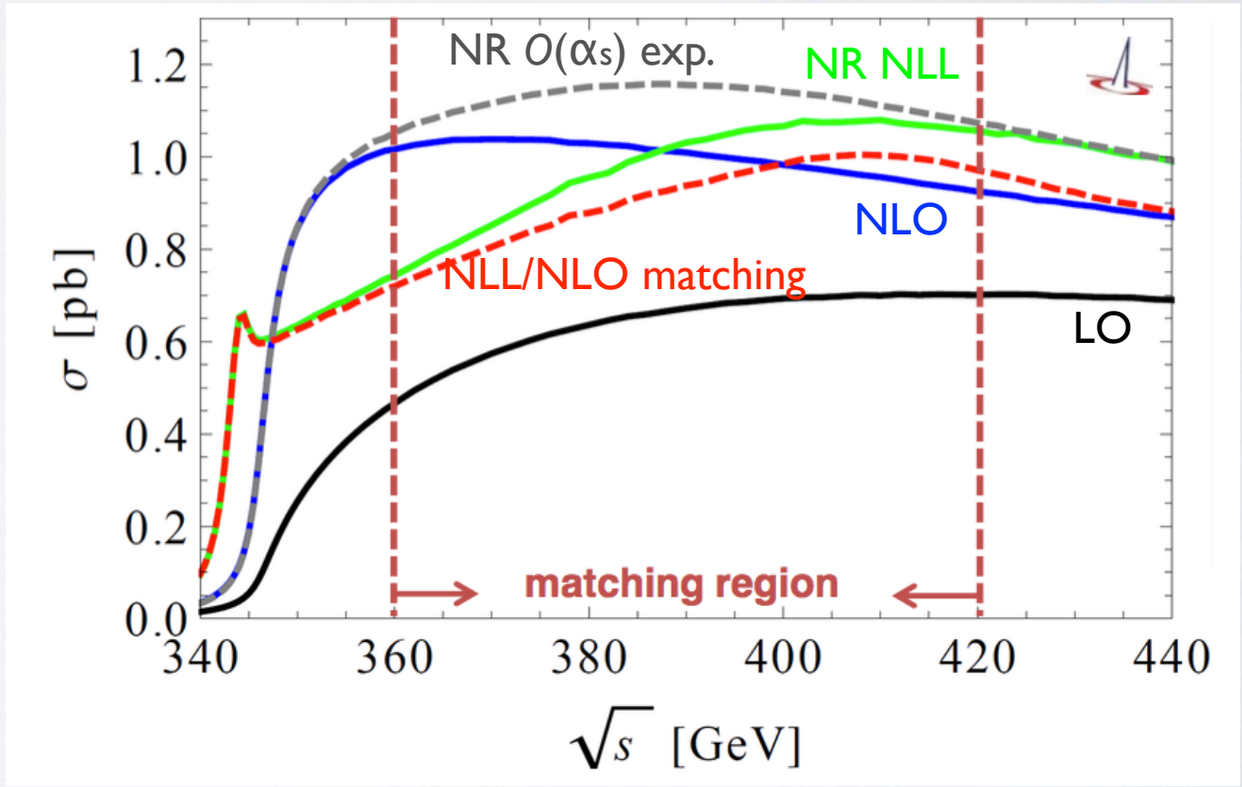
- Soft nonrel. $O(\alpha_s)$ corrections vanishing as $\log(v)$ for $v \to 1$





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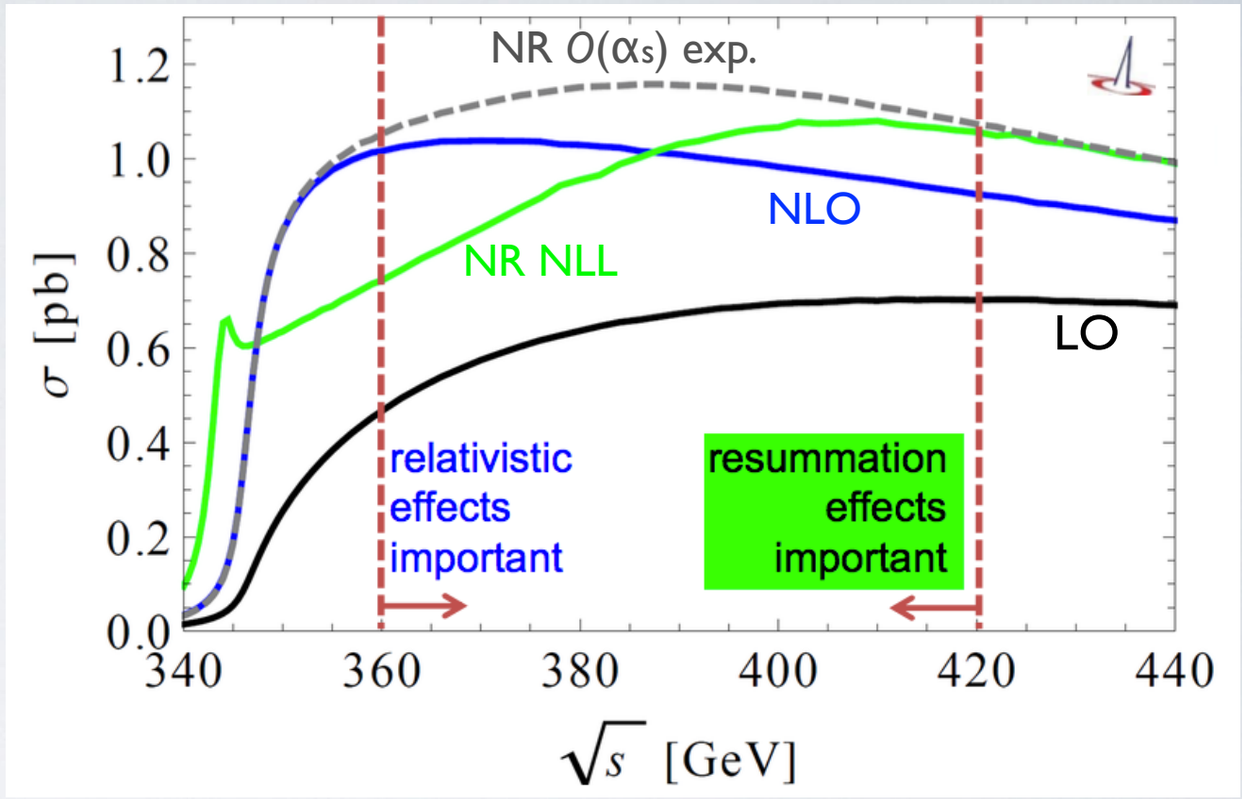

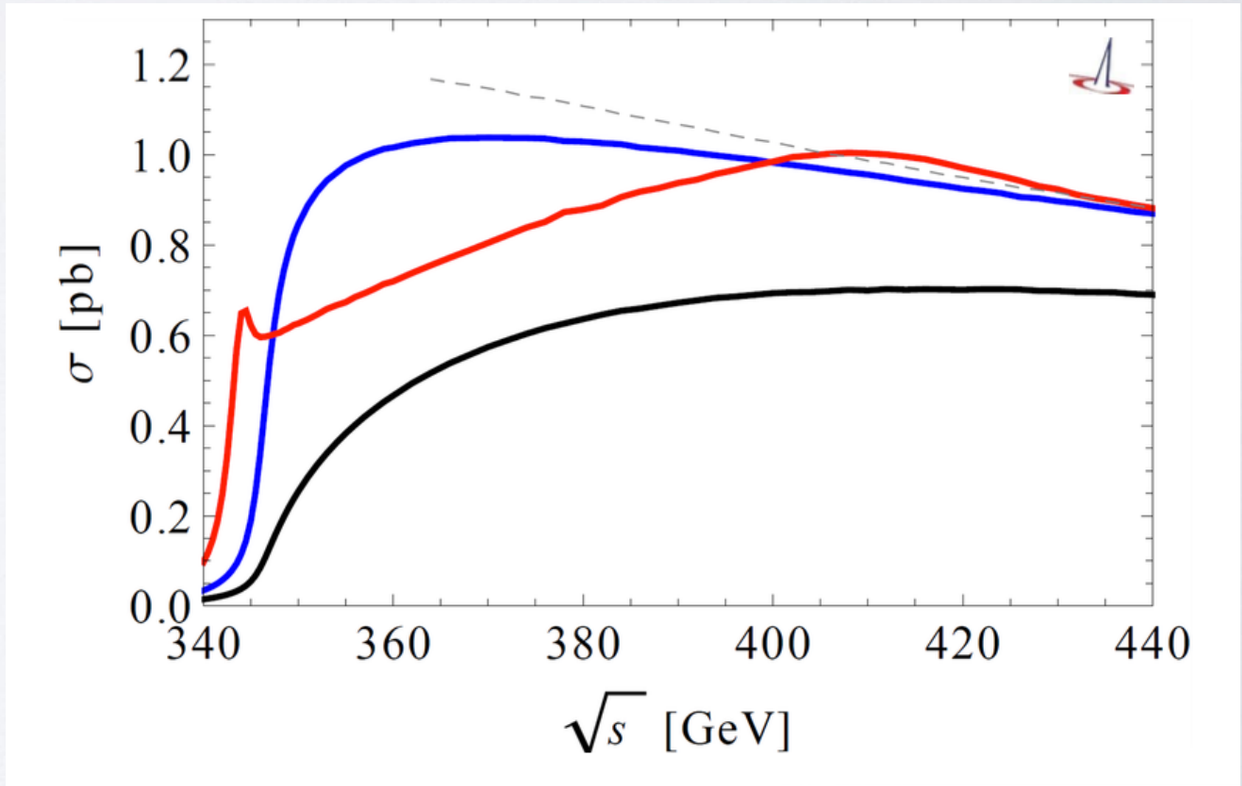

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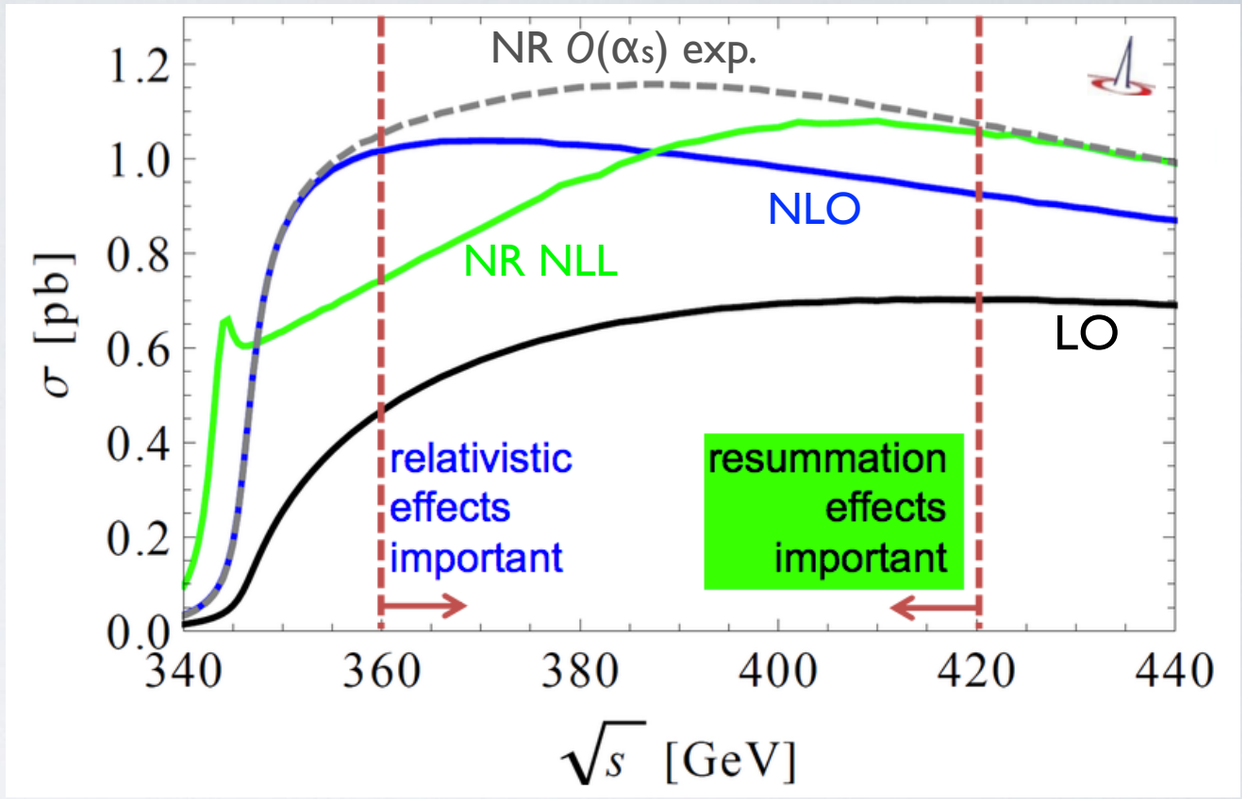
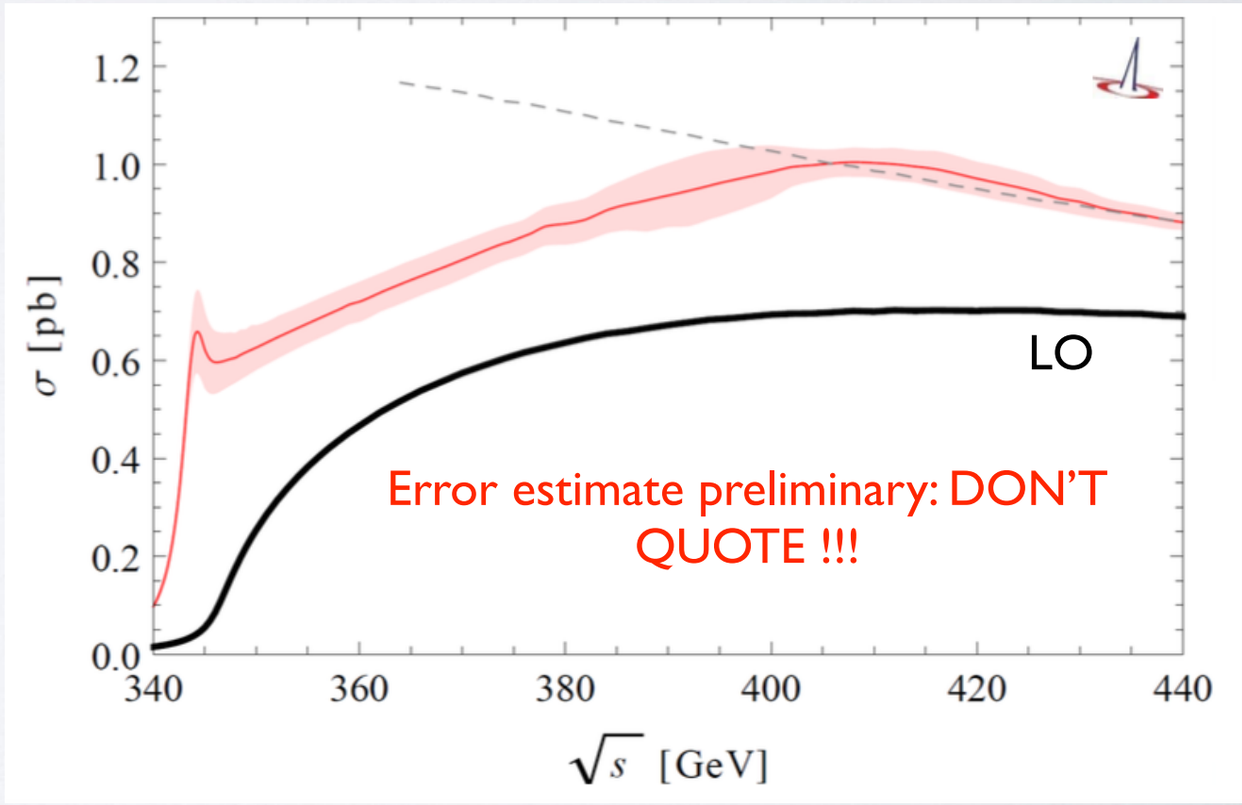
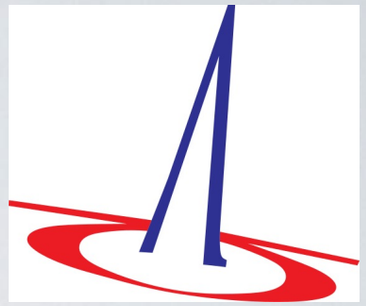
Total uncertainty: **matching and *h-f* variation band**





Conclusions & Outlook



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- NLO automation: reals and subtraction terms (FKS) [+ virtuals externally] → WHIZARD 3.0
- allows to produce NLO fixed-order histograms
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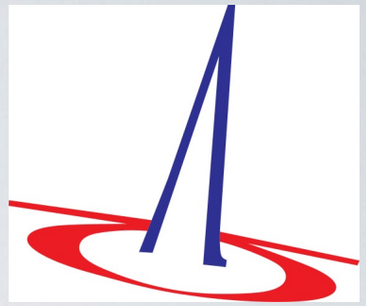

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Pictorial summary: loops, legs, and subtractions

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BACKUP SLIDES:

Phase Space Setup

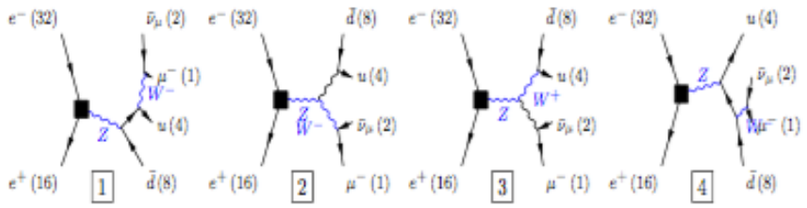
WHIZARD algorithm: heuristics to classify phase-space topology, adaptive multi-channel mapping $\Longrightarrow$ `resonant, t-channel, radiation, infrared, collinear, off-shell`

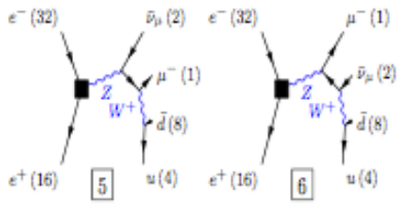
WHIZARD phase space channels

Process: `cc10` ($e^-e^+ \to \mu^-\bar{\nu}_\mu u\bar{d}$)
Color code: resonance, t-channel, radiation, infrared, collinear, external/off-shell

Grove 1

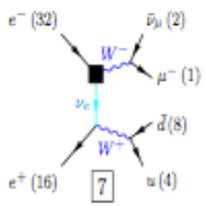
Multiplicity: 1
Resonances: 2
Log-enhanced: 0
t-channel: 0





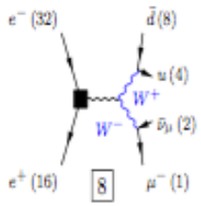
Grove 2

Multiplicity: 2
Resonances: 2
Log-enhanced: 1
t-channel: 1



Grove 3

Multiplicity: 2
Resonances: 2
Log-enhanced: 0
t-channel: 0

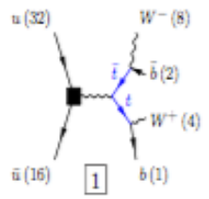


WHIZARD phase space channels

Process: `qqttdec` ($u\bar{u} \to b\bar{b}W^+W^-$)
Color code: resonance, t-channel, radiation, infrared, collinear, external/off-shell

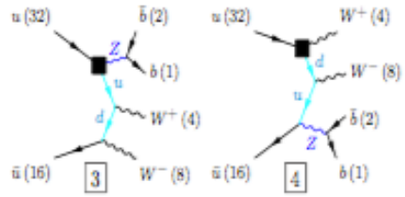
Grove 1

Multiplicity: 2
Resonances: 2
Log-enhanced: 0
t-channel: 0



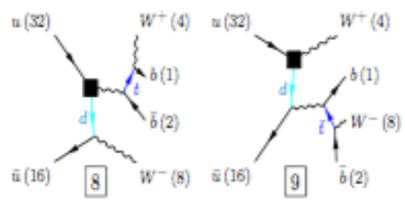
Grove 3

Multiplicity: 3
Resonances: 1
Log-enhanced: 2
t-channel: 2



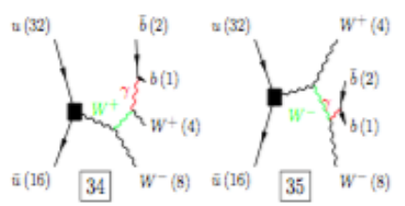
Grove 6

Multiplicity: 3
Resonances: 1
Log-enhanced: 1
t-channel: 1



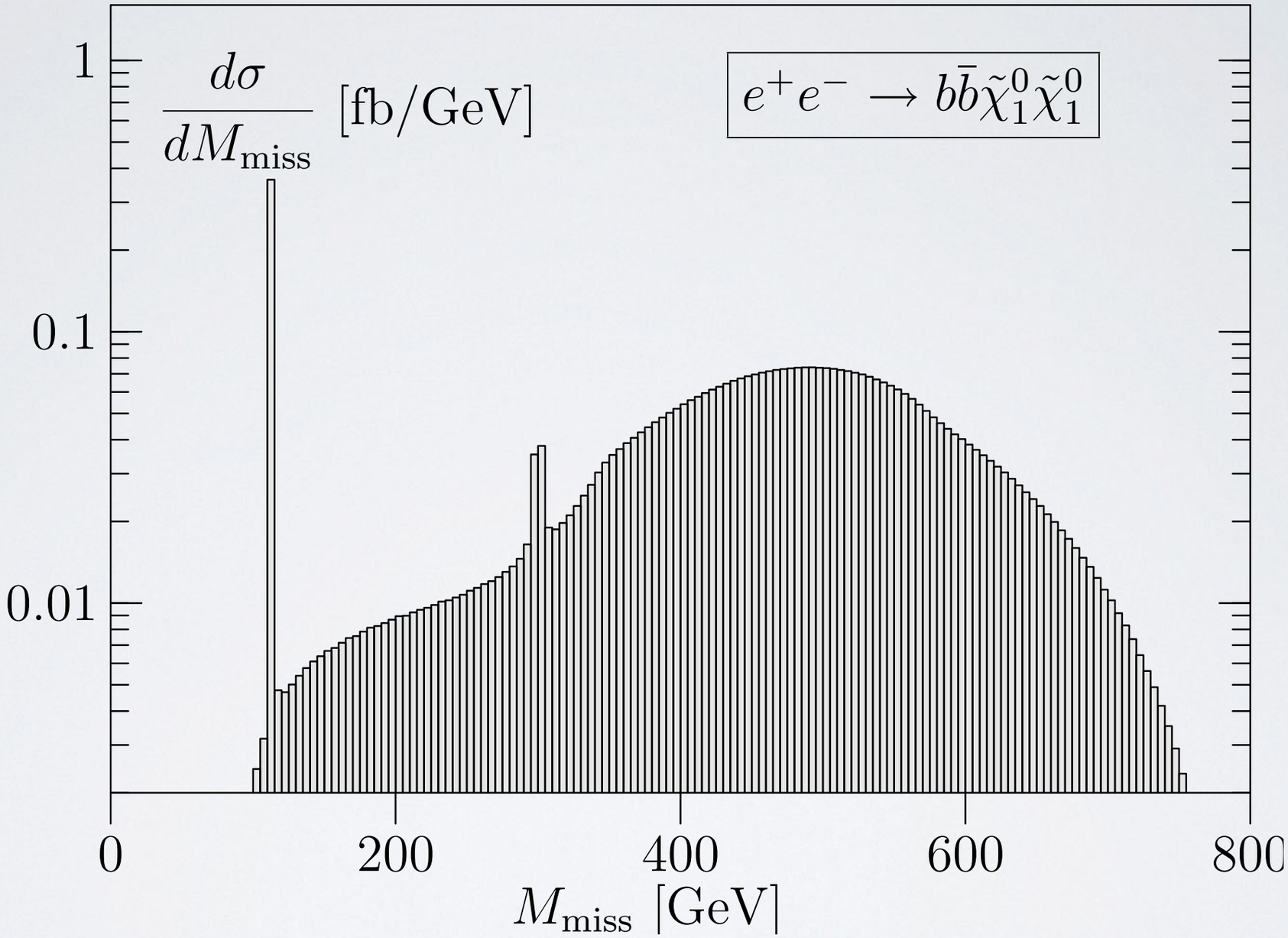
Grove 19

Multiplicity: 4
Resonances: 0
Log-enhanced: 2
t-channel: 0



Complicated processes: factorization into production and decay with the `unstable` option

Why care about beamstrahlung / ISR ?



Why care about beamstrahlung / ISR ?